SCREENING TEXAS A&M GERMPLASM AND ENVIRONMENTS FOR HYBRID WHEAT POTENTIAL

A Thesis

by

BRANDON JAMES GERRISH

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Chair of Committee, Amir M.H. Ibrahim
Committee Members, Shuyu Liu
Jackie C. Rudd
Head of Department, David Baltensperger

December 2015

Major Subject: Plant Breeding

ABSTRACT

Higher wheat prices, performance potential of hybrids, and the availability of new next generation sequencing has sparked a renewed interest in the development of hybrid wheat. The main advantages of hybrids are higher biomass and yield, longer grain fill periods, enhanced yield stability, vigorous root systems, and increased resistance to biotic and abiotic stresses.

The purpose of this research was to investigate key components that are necessary for a hybrid wheat program. The objectives of this study were to 1) gain a better understanding of the environments and germplasm by utilizing yield data from 2008-2012 advanced variety trials and biplot analysis, 2) determine the contribution of parents in early observation nursery and advanced yield trials by utilizing the existing data from 2009-2012 and 2011-2014 data, respectively, and 3) estimate heterosis and combining ability among a selected set of TAM lines based on phenotypic traits. The third objective was achieved by evaluating the F_1 generation from a half-diallel cross for yield and its components in a growth chamber.

The biplot analysis of yield data from 2008-2012 advanced variety trials showed high significant differences amongst environments, varieties, and variety-by-environment interaction. Three mega-environments within Texas were identified and several environments were found to be potentially suitable for hybrid wheat production as they produced high yields each year. ‘Duster’ was found to be the highest yielding and most stable cultivar across environments while ‘Fannin’ was the lowest yielding and unstable. ‘TAM 112’ and ‘TAM 111’ were among the top parental contributors in developing new lines, while ‘Pastor’ had the best mean yield performance among cultivars. The F_1 generation from the diallel

cross showed significant differences ($P<0.05$) in all factors of yield and its components. Three of the eight parents (TAM 113, TAM 305, TAM 401) were found to have highly significant ($P<0.005$) positive general combining ability (GCA) effects for grain yield while three others (TAM 111, TX10D2230, Sturdy 2K) were found to have highly negative GCA effects. In the F_2 generation, significant differences ($P<0.05$) were found for grain yield. None of the parents were found to be significant for GCA.

ACKNOWLEDGEMENTS

"The achievements of an organization are the results of the combined effort of each individual"- Green Bay Packer Coach Vince Lombardi. A common feature of successful programs is teamwork, and likewise my research would not have been possible without the support of many individuals. I would first like to thank my committee chair, Dr. Amir M.H. Ibrahim, for providing me the opportunity to complete my Masters Degree. I greatly appreciated his time and guidance. Likewise, I would like to thank my committee members, Dr. Jackie C. Rudd, Dr. Clark Neely, and Dr. Shuyu Liu. I would also like to thank the other members of the Texas A&M University Wheat Breeding team including research assistants Dr. Geraldine Opena and Bryan Simoneaux, assistant research scientist Dr. Nithya Subramanian, and research associate Dr. Fei Wang. Graduate students Silvano Ocheya, Jordanna Tadlock, and Russ Garetson were of great assistance as was undergraduate student worker Avery Lewis. I would also like to give a special thanks to the Texas A&M AgriLife Monocot Improvement Initiative for funding my research. Finally, I would like to thank my parents and entire family for their continuous support. I have enjoyed conducting this research and have gained experience in numerous areas that will benefit me greatly in the years to come.

NOMENCLATURE

AA	Amarillo Advanced
ANOVA	Analysis of Variance
AOBS	Amarillo Observations
CHA	Chemical Hybridizing Agent
CMA	Cytoplasmic Male Sterility
GCA	General Combining Ability
SCA	Specific Combining Ability
SOBS	Southern Observations
STA	South Texas Advanced
TAM	Texas A&M
UVT	Uniform Variety Trials

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER I

INTRODUCTION AND REVIEW OF LITERATURE

Introduction

Wheat (*Triticum aestivum* L.) is one of the most important cereal crops with global production projected to exceed 720 million tons in 2015 (FAOSTAT, 2015). Such production is possible due to its wide adaptation to different climatic conditions, from 67°N in Scandinavia to 45°S in Argentina as well as elevated regions in the tropics and sub-tropics (Feldman, 1995). Two billion bushels of wheat were produced in the US in 2014 (USDA-ERS, 2015) which represented almost 8% of the world's total wheat production for that year. In 2014, Texas grew 67.5 million bushels of hard red winter wheat and averaged 30 bushels/acre (USDA-NASS (a), 2015). The unique properties of dough made from wheat flours allow it to be produced into a wide range of products such as breads, cakes, pasta, and other processed foods (Shewry, 2009). These products account for 20% of the worldwide caloric intake and a similar proportion of daily protein for about 2.5 billion people in less-developed countries (Braun et al., 2010). A problem exists, though, as the world population is projected to reach 9.6 billion by 2050 and at the current rate of yield increase (0.9% per year), only around a 38% increase in wheat production is possible in that span (Ray et al., 2013). Hybrid wheat offers a possible solution as it has the potential to significantly increase yields and create new breeding opportunities (Whitford et al., 2013).

Exploration into the potential of utilizing hybrid vigor in wheat began in the early 20th century and has seen renewed interest in recent years. Serious research began in the 1960's from both the private and public sectors but was haltered primarily due to the low prices of wheat. At that time, wheat grain was only selling for $2.00 per bushel and based on maximum heterosis of 10-15%, a hybrid had to out-yield a variety by 25% in order to justify the additional cost of hybrid seed (Reitz, 1965). One reason for the renewed interest in hybrid wheat is the general trend of wheat prices increasing since the early 2000's (Index Mundi, 2015). In contrast to the low prices seen in the 1960's, rates received by farmers for wheat in 2011 averaged $7.44/bushel (Agriculture Marketing Research Center, 2012). Another important factor is the availability of new next generation sequencing technology that reduces the time and cost of selecting parents with good combining ability. It has been suggested that the most effective heterosis occurs when there is wide genetic divergence between the parents (Coors and Pandey, 1999), and molecular markers such as simple sequence repeats (SSRs) have been used to measure genetic distance between lines and heterotic groups (Xu et al., 2002; KeHui et al., 2006). The performance potential of hybrid wheat is a third reason for the renewed interest. The advantage of hybrids over inbred cultivars include higher biomass and yield, longer grain fill periods, enhanced yield stability, vigorous root systems, and increased resistance to biotic and abiotic stresses (Saaten-Union, 2012; Foster, 2011; Cisar and Cooper, 2002). New breeding methodologies along with advances in technology provide the tools needed for hybrid wheat development moving into the future.

The two essential features of any breeding program are good testing environments and diverse germplasm. About six million acres of wheat is grown in Texas every year (USDA-NASS (b), 2015) and as can be expected, abiotic and biotic stresses are highly variable across regions and years. In order to discern the level of variability that exists in the germplasm, over 30 testing locations with different temperature, precipitation and soil types are used annually and the data collected is used to select and develop superior varieties.

Statistical data analysis tools such as SAS and biplots can assist in appropriately evaluating germplasm and testing environments (Yan and Tinker, 2006) and varieties with biotic and abiotic stress tolerance, good yields and yield stability can be identified for potential use in a hybrid wheat program. The identified cultivars could be used to develop hybrid wheat or to create new cultivars that will be considered for hybrid wheat production. It must also be taken into account that wheat is naturally a self-pollinating crop, and for developing hybrid wheat, adequate cross-pollination attributes are necessary. Research on floral characteristics of wheat such as anther extrusion of males and glume opening, stigma size, featheriness duration and exertion of females is currently being done in our program. Therefore, the goal of this study was to evaluate our testing environments and germplasm as well as to screen TAM wheat germplasm for heterosis.

The main objective of this research is to investigate key components that are necessary for a hybrid wheat program. The specific objectives are to: 1) Evaluate the importance and contribution of each variety trial location, 2) Evaluate TAM germplasm for combining ability, and 3) Estimate heterosis and combining ability among a selected set of TAM wheat lines based on phenotypic traits of the F_1 and F_2 generations of an 8x8 diallel cross.

Origin and Domestication of Bread Wheat

Wheat (*Triticum aestivum* L.) has been cultivated for more than 10,000 years at its geographic center of origin in southwestern Asia (Sleper and Poehlman, 2006). The earliest cultivated forms were diploid einkorn and tetraploid emmer species (Shewry, 2009). Hexaploid bread wheat appeared around 9000 years ago and at that time cultivation had spread to the Near East (Feldman, 2001). The earliest cultivations were land races that were selected by farmers from wild populations due to their superior yields and other characteristics (Shewry, 2009). There are two important genetic traits that separate domesticated wheat from their wild relatives. The first trait is the shattering of the spike at maturity which, although important for ensuring seed dispersal, is not a desirable trait for cultivars. It is now known that the difference between shattering and non-shattering is due to mutations in the Br (brittle rachis) locus (Nalam et al., 2006). The second trait is the change from hulled forms that adhere tightly to the glumes to free-threshing naked forms where the seed can be easily removed from the glumes. The free forms arose from a dominant mutant at the Q locus which modified the effects of the Tg (tenacious glume) locus (Simons et al., 2006; Jantasuriyarat et al., 2004; Dubkovsky and Dvorak, 2007). Post domestication, wheat spread both northward to modern day United Kingdom and Scandinavia by around 5000 B.C. and eastward into central Asia by about 3000 B.C. (Shewry, 2009). Currently, around 95% of wheat grown worldwide is hexaploid bread wheat while the remaining 5% is mostly tetraploid durum wheat (Shewry, 2009).

The *Triticum* species are grouped into three ploidy classes that include diploid (2n=2x=14), tetraploid (2n=4x=28), and hexaploid (2n=6x=42) species (Sleper and Poehlman, 2006). Diploid species contain only the A-genome and have 14 chromosomes. Durum (*T. durum*) and emmer (*T. turgidium*) wheat, which are tetraploid species, are comprised of the A and B genomes and contain 28 chromosomes. The hexaploid species, common bread wheat (*T. aestivum* L.), contain the A, B, and D genomes and have 42 chromosomes. Research has been conducted to determine the origin of each of these genomes. It has been concluded that the A-genome donor to hexaploid wheat, as well as other polyploidy wheats such as *T. timopheevii* and *T. zhukovskyi*, is most likely a diploid wheat known as *T. urartu* (Feuillet et al., 2008; Ling et al., 2013). This species resembles todays cultivated wheat in morphology and in spike and seed development more than the other genome donators of hexaploid wheat (Ling et al., 2013). Although there have been many publications trying to determine the origin of the B-genome, the true source is still relatively unknown. The B-genome is closely related to the S-genome of the Sitopsis section of the genus *Aegilops* L. and evidence points to the species *Ae. speltoides* as being the B-genome donor (Feuillet et al., 2008; Haider, 2013). However, some experiments point to other possible donors such as *T. searsii* (Nath et al., 1983) inferring that more research is needed to positively identify the donor of the B-genome. The species *Aegilops tauschii* has been identified and generally accepted as the D-genome donor (Kihara, 1944; Lagudah and Halloran, 1987). There has been little deviation in the D-genomes of hexaploid wheat (*T. aestivum*) and diploid wheat (*Ae. tauschii*) since the hybridization occurred (Shewry, 2009).

It is widely believed that modern bread wheat was formed as the result of multiple hybridization events (Eversole et al., 2014; Feuillet et al., 2008) (Figure 1.1). The first event was between the diploid A-genome donor (*T. urartu*) hybridizing with the unconfirmed B-genome donor leading to the formation of the tetraploid wheat known as emmer (*T. turgidum*) (AABB genomes, 2n=4x=28) (Feuillet et al., 2008; Peng et al., 2011). This new species was domesticated and is generally higher yielding, more vigorous, and adapted to a broader range of environments than either of its ancestors (Feuillet et al., 2008). One subspecies, *T. turgidum* ssp. *durum*, is still of great economic importance today as it is widely grown as a pasta wheat cultivar (Feldman, 2001). The second hybridization event was between the tetraploid wheat and the D-genome donor *Ae. tauchsii* to form the hexaploid species *T. aestivum* (AABBDD, 2n=6x=42) (Matsuoka, 2011). It is believed that this event took place southwest of the Caspian Sea in modern day Iran. The two hybridization events were unique as chromosome doubling occurred creating fertile hybrids capable of reproducing rather than the sterile hybrids that would result in most circumstances (Feuillet et al., 2008). The addition of the D-genome brought in new alleles adapted to central Asia allowing for even more expansion of wheat cultivation (Feuillet et al., 2008) and also improved bread making properties by encoding for proteins that restore the softness of the grain endosperm (Chantret et al., 2005). The International Wheat Genome Sequencing Consortium (IWGSC) recently conducted a study comparing gene sequences of bread wheat with its closest existent relatives that are believed to be the contributors of the A, B, and D genomes. Results showed that there was limited loss of genes during the hybridization events and frequent gene duplications had occurred when the different genomes came together resulting in repeated sequences comprising more than 80% of the genome (Eversole et al., 2014).

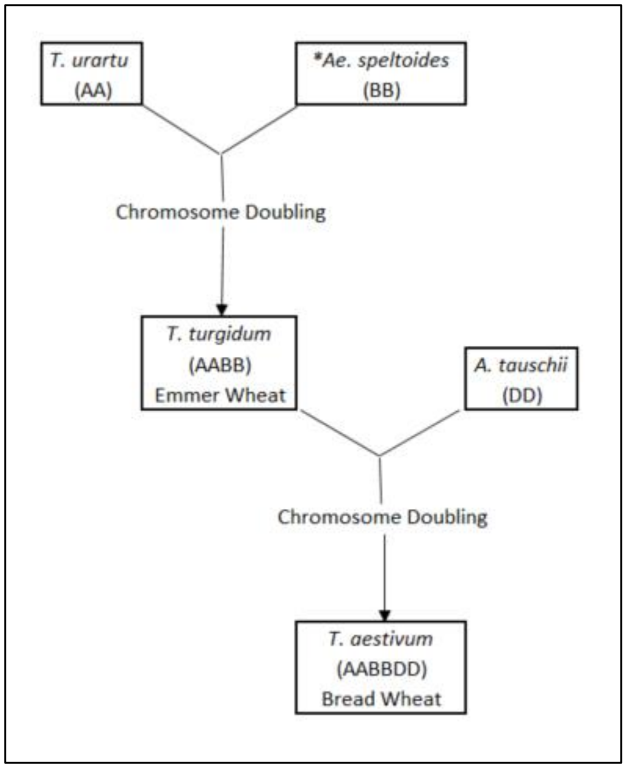

Figure 1.1 Evolution of modern bread wheat
*True donor of B-genome speculated to be *Aegilops speltoides* but unconfirmed.

History of Hybrid Wheat

The investigation into utilizing hybrid vigor in wheat began in the early 20th century and serious development began in the 1960s by both the private and public sectors including Texas A&M Agrilife Research (Porter et al., 1964; Kherde et al., 1967; Porter et al., 1989). The first major step in developing hybrid wheat came in the early 1960s when fertility-restoring genes were successfully transferred from *Triticum timopheevii* to common wheat via substitution backcrossing (Wilson and Ross, 1962). This cytoplasmic male sterility (CMS) system was used to create the first commercial hybrid wheat which was marketed in the U.S. by DeKalb in 1974 and Pioneer Hi-Bred International in 1975 (Edwards, 2001). The use of chemical hybridizing agents (CHAs) for inducing male sterility in wheat was initiated in 1960 (Chopra et al., 1960) and in 1985 the first commercial hybrid wheat developed from this system was registered in France by the American chemical firm Rohm and Hass. However, due to the low market prices of wheat in the 1960s and continuing into the next decade, many hybrid program efforts were abandoned. During that time, wheat was only selling for around $2 per bushel and based on a maximum heterosis of 10-15%, a hybrid would have to out-yield a variety by 25% to justify the additional cost of hybrid seed (Reitz, 1965). Some hybrid research did continue and since then programs have been initiated in other countries around the world such as France, South Africa, Australia, India, and China. New hybrid cultivars were created in the 1990's using the CHAs Genesis, which was developed by Monsanto (Cisar and Cooper, 2002) as well as Croisor®100 , which was developed by Dupont's Hybrinova program (Allen-Stevens, 2012). The performance of these agents brought hope for economically viable seed production.

Hybrid wheat production is continuing to grow around the world. The hybrid programs of Monsanto and Dupont were sold to the European based company Saaten-Union in the early 2000s (Allen-Stevens, 2012). Their varieties now occupy 80% of the hybrid seed of today's world market (Saaten-Union, 2012). The chemical sterilant Croisor 100 received French marketing authorization in 2003 and is the only European country where the chemical is registered and therefore all seed must be made there and transported to other countries. Hybrid wheat cultivation in Europe reached approximately 250,000 ha in 2012 (Saaten-Union, 2012) and is increasing each year. There has been a renewed interest in hybrid wheat in the United States as well with companies such as Monsanto, Bayer Crop Science, Syngenta, and Limagrain competing to release a cultivar. This renewed interest is due to several factors such as higher market prices of wheat, the performance potential of hybrids, and the availability of new next generation sequencing technology that can dramatically reduce the cost and time of selecting parents with good combining ability. Although it appears that no hybrid wheat cultivars are currently available in the United States, it is believed that one could be released very soon. Syngenta's Agripro program is working on transferring the CMS system of their European hybrid barley program into wheat with hopes of bringing commercial hybrid seed to U.S. farms by 2020 (Griekspoor, 2013).

Induction of Male Sterility

The first method used for inducing male sterility for hybrid wheat production was the CMS system. It is well known that the wild tetraploid species *Triticum timopheevii* is a source of cytoplasmic male sterility (Sleper and Poehlman, 2006) and was first described as a feasible CMS system by Wilson and Ross (1962) who reported that it caused no major negative effects on agronomic and quality characteristics. Although sources of male sterility have been identified in other species of *Triticum* and *Aegilops*, almost all CMS breeding has been done with *T. timopheevii* due to the deleterious effects seen from many other cytoplasms and those that may work show no advantage over *T. timopheevii* (Virmani and Edwards, 1983). However, another CMS system using *Ae. kotschyii* and *Ae. variabilis* (Mukai and Tsunewaki, 1979) has received significant attention as well. These systems use a three-line system (A, B, and R lines) for the production of hybrid seed (Figure 1.2).

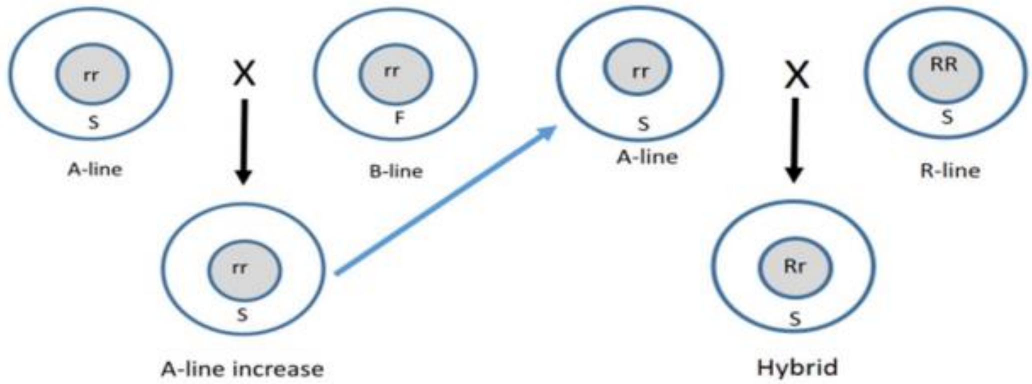

Figure 1.2 Hybrid wheat production using a CMS three-line system. *Figure courtesy of Dr. P. Stephen Baenziger, University of Nebraska.*

The A line is usually derived from *T. timopheevii* and contributes male-sterility in both the genes (rr) and the cytoplasm (S). The B line has genes for sterility (rr) but is fertile due to its cytoplasm (F) and is known as the maintainer line, which is crossed with the A line to produce male sterile progeny (rr-S) and is referred to as the A line increase. The male sterile progeny are then crossed to a restorer (R) line, known as the restorer line, which contains dominant restorer genes (RR-S) to form the fertile hybrid seed (Rr-S) (Dr. P. Stephen Baenziger- Personal Communication). The CMS system is utilized in India (Matuschke et al., 2007) and partially in the United States, China, and Australia (Saaten-Union, 2012).

Another method used for inducing male sterility is the CHA system in which a chemical sterilant is used to suppress pollen production or viability. An ideal CHA would have many attributes including selectively inducing pollen sterility without affecting female fertility, sufficiently sterilizing both early and late tillers, and have a broad window for application to combat adverse weather conditions (Edwards, 2001). Although a chemical that meets all desired criteria has not yet been developed, CHAs are the predominant method for commercial hybrid wheat (Edwards, 2001). The most common, if not exclusive, sterilant used today appears to be Croisor 100 (active ingredient Sintofen) which is directly supplied to hybrid wheat seed producers by Saaten-Union (Saaten-Union, 2012). It does not appear that Genesis is still in use, possibly due to environmental hazards (Iskra et al., 2013). Another chemical known as DPX 3778 was experimented with in the late 1970's and was found to be far more effective in spring wheat than in winter wheat (Johnson and Brown, 1978). Although it does not appear that this chemical was ever commercially marketed, it showed that CHAs could be used to control pollination while having limited side effects on plant development. Today, almost all hybrids in Europe appear to be produced chemically.

There are advantages and disadvantages to each of these systems. The CMS system is available to all breeders as there are no intellectual property issues and obtaining licensing, and government approval in some countries, for a CHA can be quite costly. This system also provides a more consistent seed set due in part to increased duration of stigma receptivity over the CHA system (Edwards and Dorlencourt, 1994) which ultimately results in lower seed costs (Saaten-Union, 2012). However, the development of restorer lines is time consuming and at least three genes are required for full pollen fertility restoration in some environments (Edwards, 2001). The time needed to develop and increase a CMS line contributes to the cost and time requirements of this system (Edwards, 2001). The greatest advantage of CHAs over the CMS system is that breeders can test larger numbers of parental lines for GCA and SCA (Edwards, 2001). Thousands of crosses can be performed each year increasing the chance of finding a good hybrid (Saaten-Union, 2012). The time delay seen in the CMS system is avoided and a new hybrid can be released in five or six years. However, the cost of the chemical as well as a fairly high production failure rate increases the expenses of this system resulting in higher seed costs. Additionally, an overdose of the CHA will further reduce seed set and profits (Cisar and Cooper, 2002).

Numerous other male sterility systems have been proposed. A two-line system using photoperiod-sensitive cytoplasmic male sterility (PCMS) was reported by Murai and Tsunewaki (1993). Using the interaction between the nuclear genome of common wheat (*T. aestivum*) with *Ae. crassa*, almost complete male sterility could be achieved in long-day conditions of 15 hours or more while producing high male fertility under short day conditions of 14.5 hours or less (Edwards, 2001). Another system known as the XYZ system (Driscoll, 1972) was developed using an "alien chromosome" for carrying the male-fertility gene and was later modified (Driscoll, 1985) to a two line system where no X-line is used and an isochromosome is used to carry the male-fertility gene. Zhang (1998) utilized this approach as a model in developing a two-line system using photo-thermo sensitive genic male sterility involving the alien chromosome 4E. Other research has been conducted involving the 4E chromosome for producing hybrid wheat (Zhou et al, 2006). Another possible solution is the use of biotechnology, which becomes more plausible with the rapid increase of advanced technologies. Research is currently underway into an anther-specific promotor, a pollen-killing gene, and an antidote or restorer which can be used to inhibit pollen formation or viability thus creating a male-sterile plant (Edwards, 2001).

Hybrid Wheat Breeding Methodology

Precise techniques and conditions are required for optimal hybrid wheat seed production. The stability, yield, and resulting cost of hybrid seed will be significantly impacted by the environment (Cisar and Cooper, 2002). Environmental conditions that consistently produce high yields, usually those under irrigation, as well as reliable wind patterns during pollination will help to lower the costs of hybrid seed (Cisar and Cooper, 2002). It has been suggested that seed production should take place in cooler climates or higher altitudes as a way to improve pollen viability (Edwards, 2001; Cisar and Cooper, 2002). The Pacific Northwest and western high plains regions have been identified as the best candidates for winter wheat (Cisar and Cooper, 2002) and parts of Arizona and California for spring wheat (Edwards, 2001). The seed grower must be knowledgeable and follow a strict protocol in order to maximize the success of hybridization (Saaten-Union, 2012). The two parental lines are grown in alternating strips; 3-8 meters wide for female strips and 3-4 meters wide for the male strips (Saaten-Union, 2012). These strips should be planted perpendicular to the regular wind pattern in order to increase pollen dispersal and areas with lower winds may require narrower female strips and a higher male to female ratio (Cisar and Cooper, 2002). It is critical to ensure that pollinators are in close proximity to the seed plant as it has been shown that seed set drops significantly when the two are more than twelve meters apart (Cisar and Cooper, 2002). One study concluded that a 2:1 male sterile to pollinator ratio to be more effective in most situations (Virmani and Edwards, 1983). The seeding rate varies for the parents as well. The pollinator is grown at a low seed rate to promote tillering and therefore extend the pollination period whereas the seed plant is grown at a high seed rate to limit secondary tillers and minimize growth stage differences for better efficiency in CHA systems (Cisar and Cooper, 2002; Saaten-Union, 2012). Application of the chemical sterilant (if used) can vary between brands. Genesis should be applied between growth stages 8.0 and 9.0 on the Feekes scale which is when the flag leaf is emerged about 50% (Cisar and Cooper, 2002) whereas Croisor is applied when the developing spike is within a specified range of length (Edwards, 2001). The chemical is applied only on the female strips and in favorable conditions as it needs a 24-hour rain-free period and excessive wind may cause drift to pollinator plants (Cisar and Cooper, 2002). When using the CHA system, yields average only about 50% of what would typically occur without sterilization (Saaten-Union, 2012). Several checks are put in place to ensure that seed production is occurring through hybridization and not from self-fertilization. In order to be marketed as a hybrid, at least 90% of the harvested grain must develop as a result of cross-fertilization (Saaten-Union, 2012). Often, at regular intervals, twenty or more wheat heads from the male sterile strips are put into covered cages, which are air and water but not pollen permeable, and checked post-pollination for the presence of grain (Saaten-Union, 2012). If no grain is present on the heads then it confirms that the plants have been sterilized and conversely if grain is present then those plants, and possibly the entire strip, have arisen from self-pollination. Grain electrophoresis can also be performed as an additional check if some doubt exists after harvest (Saaten-Union, 2012).

Establishing Good Germplasm and Testing Environments

The initial step in any breeding program is to develop heterotic groups (Sleper and Poehlman, 2006). Wheat is a self-pollinating species with an outcrossing rate up to six percent (Hucl, 1996). For developing hybrid wheat, adequate outcrossing attributes are necessary. Cross-pollination in wheat is influenced by floral characteristics such as stigma size, anther size, anther extrusion, pollen number, and pollen viability (Singh et al., 2010). Therefore, it is important to select genotypes for floral characteristics that are essential in potential pollinators or seed plants. Both parents need to have a wide glume opening which is commonly referred to as open flowering. The male-sterile parent is required to have a wide angle of glume separation with a long duration of opening, and although this is less significant for the pollinator, the glume separation must be sufficient to allow for anther extrusion (De Vries, 1970). After comparison of several experiments, De Vries (1970) concluded that both parents should be awnless in order to get maximum seed set. Larger sizes, longer durations of receptivity, and farther exsertion of the stigma are needed in order to increase the chances of cross pollination (De Vries, 1970). Additionally, in CHA systems, females will need to be selected based on their response to the sterilizing agent (Allen-Stevens, 2012). In general, one of the largest differences between self and cross pollinated species is the amount of pollen produced. Therefore, an integral part of a hybrid wheat breeding program is to select genotypes with high pollen production (De Vries, 1970). The viability of pollen for most plants in the Poaceae family is short (Lichte, 1957) and some attention is required in finding varieties that have longer pollen viability to ensure cross-pollination can occur. Many of these floral traits are greatly affected by the weather (De Vries, 1970) and have moderate to high heritability (Cisar and Cooper, 2002). It is also important that the male-sterile be shorter (Allen-Stevens, 2012) and flower 2-5 days earlier than the pollinator (Cisar and Cooper, 2012). This may result in plant propagation of varieties that are never marketed and used solely as hybrid parents (Saaten-Union, 2012).

It is not guaranteed that a successful hybrid will result even if all of these floral requirements are met. Finding the right parental combinations is critical as some crosses do not show any heterosis and may not even yield as much as either parent (Cisar and Cooper, 2002). It has been suggested that a wide genetic divergence between parents results in increased heterosis (Coors and Pandey, 1999), but this does not guarantee good general combining ability (GCA) between heterotic groups. Since several females can be put in close proximity to a single male but not vice-versa, the female heterotic group tends to be larger than the male pool (Saaten-Union, 2012). Therefore the use of the sum of the GCA components as a predictor of performance is resource limited (Gowda et al., 2012). The degree to which GCA is a good indicator of specific combining ability (SCA) is dependent upon the variance in GCA and SCA among heterotic pools (Gowda et al., 2012). A large genetic divergence between heterotic groups leads to a low ratio of variance in SCA to GCA and if GCA is a good indicator of SCA then lines can be thrown out earlier in the testing process (Fischer et al., 2008). The ratio of variance in SCA to GCA was found to be high in maize and hybrid wheat (Fischer et al., 2008; Gowda et al., 2012). A number of trials using diallel cross designs have been used to determine the effects of GCA and SCA on yield and other traits (Bitzer et al., 1982; Fonseca and Patterson, 1968; Boghi and Perenzin, 1994). A diallel SAS program has been developed to calculate GCA and SCA effects on plant yield (Zhang and Kang, 1997).

Another important goal of a plant breeding program is developing cultivars that are high yielding and widely adapted to different environments. Hence, testing genotypes in different environments is important to select a widely adapted cultivar. The environmental effect on genotypes plays a major role in the selection process and it is important to have environments that are discriminating between varieties. A non-discriminating testing location will show no differences between superior and non-superior varieties and therefore contributes less useful information for selecting varieties. Statistical analysis software such as SAS, which is extensively used by the USDA (Smith, 2012), is commonly used to test for statistical significance in experiments. In general, large variability of abiotic and biotic stresses can exist across regions and years requiring the use of many testing environments. Bi-plot analysis is a powerful tool for visually evaluating multi-environment data as well as assisting in better understanding the germplasm and environments used in a breeding program. Bi-plot analysis was first developed by Gabriel (1971) and first applied to analyzing agricultural data by Bradu and Gabriel (1978). Sorting environments into mega-environments that produce similar results aids breeders in targeting particular germplasm and efficiently using the resources available to them (Malla et al., 2010). Successful new varieties must show high performance and stability for yield, amongst other traits, over a wide range of environmental conditions (Becker and Leon, 1988). Given sufficient data, genotypes with high performance and stability as well as test environments that are discriminating and representative can be identified using bi-plot analysis (Yan and Tinker, 2006).

Benefits of Hybrid Wheat

The numerous benefits of hybrid wheat are the driving force for all the research being put into it. The main focus of hybrid research is the potential yield advantage of hybrids over line bred cultivars which is a result of heterosis. There has been much research into the heterosis potential of wheat since the early 1960s. In one of the earliest reviews, Briggle (1963) noted that there were varying estimates of heterosis amongst experiments, and expression of hybrid vigor was not present in all parental combinations. Another review by Johnson and Schmidt (1968) found many instances where hybrids out yielded the high parent and one instance where no advantage was found. Although some heterosis estimates are reported to be as high as 88% or more (Cisar and Cooper, 2002), realistic expectations are probably between 5%-15% (Edwards, 2001). Duvick (1999) found that heterosis levels can reach up to 30%, but these are usually the results of crosses between classes of wheat such as hard and soft red winter wheat cultivars. Longin et al. (2012) concluded that the average heterosis for yield to be around 10% as well as 7% for plant height. This heterosis is much lower than allogamous species for several reasons: 1) There is a lower degree of dominance for alleles at the QTL of interest, 2) there is a lower genetic distance among parental lines at these QTL, and 3) there is epistasis both within the same genome and amongst homeologous loci from different genomes within the wheat allopolyploid which is often termed as fixed heterosis (Longin et al., 2012). The primary source of yield gain has been reported to come from an increase in the number of grains per head (Pickett, 1993; Merkle et al., 1966). Other characteristics that have been linked to heterosis include grain weight, tillering capacity, and occasionally, days to heading (Pickett, 1993; Cisar and Cooper, 2002). Additionally it is reported, from scientific trials as well as by farmers throughout Europe, that hybrids provide greater yield consistency between years and environments and that the most prominent yield advantages are seen under difficult growing conditions such as years of drought or high disease pressure (Saaten-Union, 2012; Foster 2011).

The additional cost associated with hybrid seed has been the primary reason for the slow development of wheat hybrids and many have looked for ways to at least partially alleviate this problem. Experimental evidence suggests that hybrids can tolerate slightly reduced seeding rates due to seedling vigor and higher tillering capacity (Cisar and Cooper, 2002). Some consideration has been given to marketing F_2 seeds but this theory has been dismissed. Genes are segregating in the second generation and, as such, the genes for fertility in a CMS system are segregating which could lead to major reductions in grain yield and other factors (Edwards, 2001). First and second generation hybrid performance trials were conducted by Edwards and Dorlencourt (1994) who found that the performance advantage in the F_1 generation is almost eliminated in the second generation. After conducting a diallel trial on hybrid vigor and combining ability of soft red winter wheat, Bitzer et al. (1982)

found the F_2 generation typically did not yield half that of the F_1 generation above the midparent as would be theoretically expected. However, using F_2 and parent yield data, F_1 heterosis can be estimated (Bailey et al., 1980). This is often done as more seed is available for yield and performance potential experiments.

There are many other advantages to growing hybrid wheat besides higher yields. Research has shown that hybrid wheats have greater accumulation of dry matter with increases of up to 46% in the foliar system and 60% in the root system (Saaten-Union, 2012). Additionally, these root systems are more powerful as phytotron trials have shown a 34% increase in root volume when the plant is not receiving enough nitrogen before growth stage 30 (Saaten-Union, 2012). The additional root mass allows for a greater uptake of nitrogen and other nutrients which is important from both economic and environmental aspects. Although the grain fill period is similar to that of conventional varieties, the grain fill rate is faster for hybrids which are more efficient in their utilization of nitrogen and carbon (Saaten-Union, 2012; Foster, 2011). Trials show that the genes dealing with protein synthesis have additive effects thus allowing hybrids to have a similar protein content to their parents despite having higher yields (Saaten-Union, 2012). A study conducted by HybriTech US evaluating soft red winter wheat found most hybrids to be equally or more winter hardy than the parents (Cisar and Cooper, 2002). Edwards (2001) states that disease resistance in hybrids may be greater as incorporating resistance genes is more efficient in hybrid breeding than in developing pure lines. Many of the major genes for disease resistance (for example Pm2, Pm6, Yr3, Yr4) are dominant so in these instances hybrids can be used to combine genes that are often difficult to obtain in conventional breeding (Edwards, 2001). At the same time, hybrids have maintained the required milling and baking qualities and in most cases appear as an intermediate between the two parents although some heterosis has been observed in these traits as well (Edwards, 2001).

Molecular Markers Used in Breeding Hybrid Wheat

Besides many other benefits, the availability and use of molecular markers has greatly contributed to the renewed interest into hybrid wheat. Molecular markers may dramatically reduce the cost and time of selecting parents with good performance potential, chemical sterilant receptivity, and other beneficial traits. Markers such as single nucleotide polymorphism (SNP), simple sequence repeat (SSR), and random amplified polymorphic DNA (RAPD) have been used to measure the genetic distance between lines (Ren et al., 2013; Xu et al., 2002; Kehui et al., 2006). Further research is needed to determine if molecular markers can be used to estimate combining ability and heterotic patterns. Most of the research on hybrid wheat is coming from the private sector and only a few published reports on proprietary information such as specific molecular markers used in hybrid wheat research are available. Diversity array technology (DArT) (Rodriguez-Suarez, 2011), SSR (Zhou et al., 2005), and restriction fragment length polymorphism (RFLP) (Ma and Sorrells, 1995) markers have been used for mapping potential restoration of fertility (Rf) genes that can be exploited in CMS systems. Several Rf genes have been identified including $Rf_{6h}{}^{ch}s$ and $Rf_{1h}{}^{ch}s$ (Castillo et al., 2014) as well as $Rf\text{-}H^{t}1$, $Rf\text{-}S^{t}1$, and $Rf\text{-}Y^{c}1$ (Jiang et al., 1992). In one particular example, molecular tagging and mapping has been conducted on the thermo-sensitive male-sterile gene (*wtms1*) which affects plant fertility based on temperature (Xing et al., 2003). The use of male sterility from other species (BeiRu et al., 2008) and the blue aleurone system (Qualset et al., 2005) are based on using molecular markers which allow for clear and rapid selection amongst hybrids. It is likely that the use of molecular markers will increase as new technology and genetic maps become available.

CHAPTER II

EVALUATION OF WHEAT VARIETY TRIAL LOCATIONS AND GERMPLASM

Introduction

Texas is a very large and diverse state with wheat producing regions ranging from temperate zones in the panhandle to the sub-tropics in the south. Abiotic and biotic stresses vary not only amongst locations, but also from one year to the next at the same location. The goal of the Texas A&M AgriLife Wheat Breeding Program is to develop higher yielding wheat cultivars that are adapted to Texas and other states in the Southern Great Plains. In order to capture the level of variability that exists, and develop adapted cultivars, over 25 locations are tested across the state annually. However, due to limited resources and increasing labor and travel costs, it is imperative that redundancy is minimized and that each testing location contributes meaningful information that will be used in the variety selection process.

Several methods can be implemented in order to analyze genotypes, environments, and genotype-environment interactions. One commonly used tool is SAS statistical software which has been utilized by the United States Department of Agriculture- National Agricultural Statistics Service (USDA-NASS) in a broad range of areas for over 35 years (Aune, 2015). A biplot is a graphical display used for evaluating multi-environment data (Gabriel, 1971). A popular biplot among plant breeders, developed by Yan (2001), is the "GGE (Genotype (G) Genotype-by-environment (GE)) biplot". This biplot has been used to determine the discriminating ability and representativeness of environments, identify the best performing genotype in an environment, identify the most suitable environment for a given genotype, and determine the average yield and stability of each of the genotypes (Malla et al., 2010; Yan and Tinker, 2006). The "Average Tester Coordination" for tester evaluation biplot, which summarizes the interrelationships between test locations (Karimizadeh, 2013), is used to compare one environment to another and group homogenous locations together. Environments that provide diverse stresses and are highly discriminating will produce the most useful information to a breeding program. The "Which-Won-Where" biplot is typically used to compare genotypes and identify genotypes that performed best in each environment as well as their stability (Yan and Hunt, 2002). The most highly regarded genotypes are those that consistently produce high yields across environments.

The main objective of this study was to evaluate our state-wide wheat variety program in regards to the importance and contribution of each variety trial location and germplasm performance. Using biplot analysis, the most discriminating and/or representative testing environment as well as the best performing genotypes and their stability in each location will be determined.

Materials and Methods

Data from the uniform variety trial (UVT) was used for this study. Collaboration between faculty of Texas A&M AgriLife Research and Texas A&M AgriLife Extension Service has been ongoing since 2004 in conducting a UVT across Texas. The UVT is comprised of a uniform list of 30-35 entries that are planted annually at over 25 locations across the state. This trial has been divided into four major geographic regions which include the High Plains, Rolling Plains, Blacklands, and South/Central (Figure 2.1). The same seed source was used to plant all locations which usually consisted of three replications laid out in a randomized complete block design (RCBD). Cultural practices varied by location but were representative for each region. Plots were planted with a small plot planter under no-till or conventional till practices and in 1.5 × 4.5 meter plots. Seed treatments and additional insecticide and herbicide applications were performed with labeled pesticides as needed but fungicides were not applied so that disease resistance could be measured. A small plot combine was used to harvest the plots and yield and test weights were determined. Abiotic stress such as drought or hail damage resulted in some locations not being harvested each year. If multiple years of data were present, the mean value was used for each location. All yield data was standardized to report grain yield in kilograms per hectare.

In this study, yield data of 16 cultivars planted at 19 locations (Figure 2.1) in the UVT from 2008-2012 was used to evaluate environment and germplasm performance. Environmental performance across years and amongst locations was examined and a combined environment analysis of variation (ANOVA) was conducted using SAS v9.3 (SAS Institute Inc., 2008). Biplot analysis was conducted using the GGE biplot software. GGE biplots were used to identify mega-environments, the most and least discriminating environments, and the best, worst, and most stable cultivars across locations. Environments were evaluated based on their ability to discriminate between varieties and the mean performance of varieties planted at each location. Locations that produced similar results were grouped into mega-environments. Furthermore, the best and worst performing cultivars were identified for each mega-environment and the stability of these cultivars was also determined.

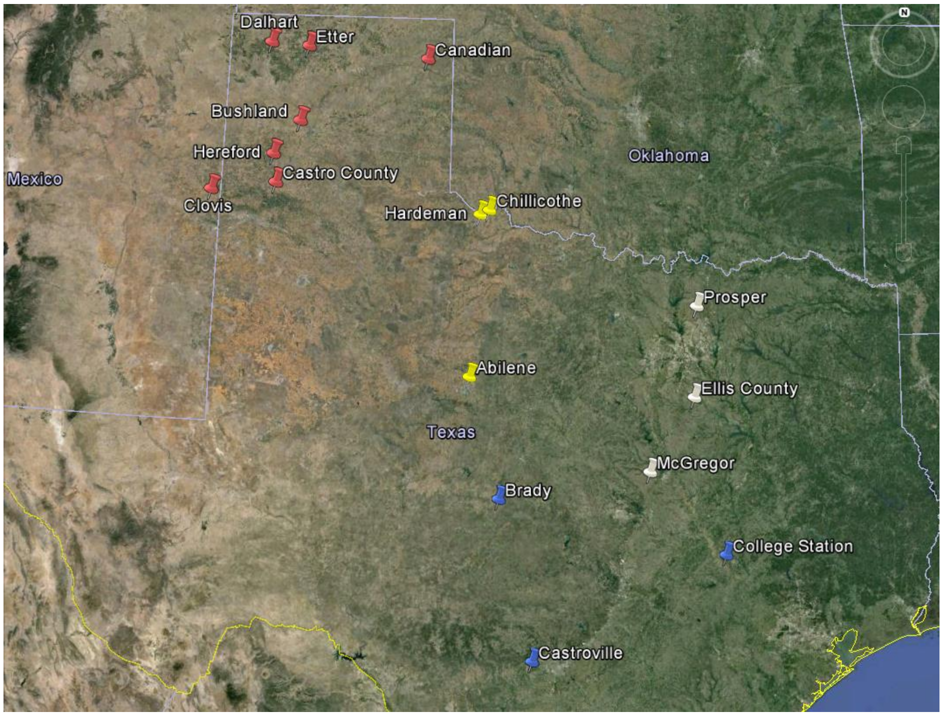

Figure 2.1 Map showing wheat testing sites by region. Red= High Plains, Yellow= Rolling Plains, White= Blacklands, Blue= South/Central Texas. Map was created using Google Earth, 2015

Results and Discussion

A combined environment ANOVA for grain yield (Table 2.1) showed highly significant differences in each source. The term “y×l” (year by location) was used to represent environments (example: College Station 2011 and College Station 2012 were considered to be two different environments). High significant differences amongst environments indicates 1) at least one location did not perform similarly from one year to another, 2) at least two locations did not perform similarly, or 3) a combination of these two, although it does not provide information on which case is present. Differences amongst environments can be better seen in Table 2.2 which shows the mean grain yield for each location across years. The ANOVA table also showed a high significant difference

(P<0.0001) between varieties indicating significant variation in yield between at least two of these varieties. Finally, the environment-by-variety interaction was found to be highly significant indicating that there was variation in the yield of genotypes amongst environments.

Table 2.1 Combined environment analysis of variance (ANOVA) for grain yield in uniform variety trials (UVT) from 2008-2012.

Source	DF	Type III SS	Mean Square	F Value	Pr>F
Env	74	1547238.8	20908.63	203.16	<.0001
rep(env)	150	15437.83	102.92	3.21	<.0001
variety	15	30789.11	2052.61	63.99	<.0001
Env*variety	1110	171934.65	154.9	4.83	<.0001
Error	2250	72177.29	32.08		

Environment= year × location, rep(env)= replications within environments, variety= differences between varieties, env*variety= variety by location interaction.

Locations that consistently produce high yields are crucial as they can greatly affect the resulting seed prices. Once a potential hybrid has undergone performance trials at several locations and is ready to be released, locations with a history of reliable performance will be used as the site for hybrid seed production. The mean grain yield data (Table 2.2) revealed several locations that will be suitable for this purpose. Comparing this data with national average yields of hard red winter wheat, which has ranged from 2266.33 to 2730 kilograms per hectare over the past four years (USDA-ERS, 2015), several locations were identified that steadily produce yields that are well above the national average. Clovis and Bushland under irrigated conditions as well as Castroville and Prosper were found to be the highest yielding locations across Texas.

Table 2.2 Mean grain yields of wheat in Texas uniform variety trials (UVT) from each testing location by year from 2008-2012.

	Grain Yield (Kg/ha)				
Environment	**2008**	**2009**	**2010**	**2011**	**2012**
Abilene	4902.5	-	3059.9	1983.9	1876.3
Bushland Dry	860.8	1116.4	2421.0	881.0	1136.5
Bushland Irrigated	1708.2	3180.9	5480.9	3987.9	4492.3
Brady	2925.4	2367.2	3671.9	1318.1	3470.1
Canadian	4606.6	1123.1	2656.4	-	-
Castroville	4310.7	3813.1	4525.9	-	3752.6
Chillicothe	2683.3	-	3369.2	874.3	2945.6
College Station	3120.4	3611.3	3685.3	-	1903.2
Castro County	2152.0	-	3752.6	4673.9	-
Clovis Dry	-	343.0	4270.4	1022.2	-
Clovis Irrigated	-	5097.6	6462.7	3873.6	6025.6
Dalhart	4673.9	2764.0	-	3100.2	4835.3
Etter Dry	786.8	1055.8	3086.8	827.2	-
Etter Irrigated	2199.1	1923.4	4001.4	3295.3	2495.0
Ellis County	3342.3	-	3732.4	2716.9	4559.6
Hereford	-	1015.5	2010.8	1049.1	-
Hardeman	-	-	3281.8	1183.6	2279.8
McGregor	3961.0	4976.5	3409.6	-	2158.7
Prosper	3678.6	-	3631.5	3799.6	4156.1

Dry= Dryland testing with no irrigation, Irrigated= Grown under irrigation, Dash (-) = Location not harvested that year.

Biplot analysis is commonly used to determine similarities amongst testing locations and identify mega-environments (Malla et al., 2010; Munaro et al., 2014; Yan et al., 2000). This was done using the ‘Average Tester Coordination’ for tester evaluation biplot (Figure 2.2). This biplot showed three clusters of locations: Etter Dry, Etter Irrigated, Canadian, Hereford, Clovis Dry, Clovis Irrigated, Bushland Dry, Bushland Irrigated, Dalhart (Cluster

1), Abilene, Brady, Castro County, Chillicothe, Hardeman (Cluster 2), College Station, Ellis County, Prosper, Castroville, and McGregor (Cluster 3). These clusters were determined to be separate mega-environments identified as the High Plains (cluster 1), Rolling Plains (cluster 2), and Blacklands/ South Texas (cluster 3).

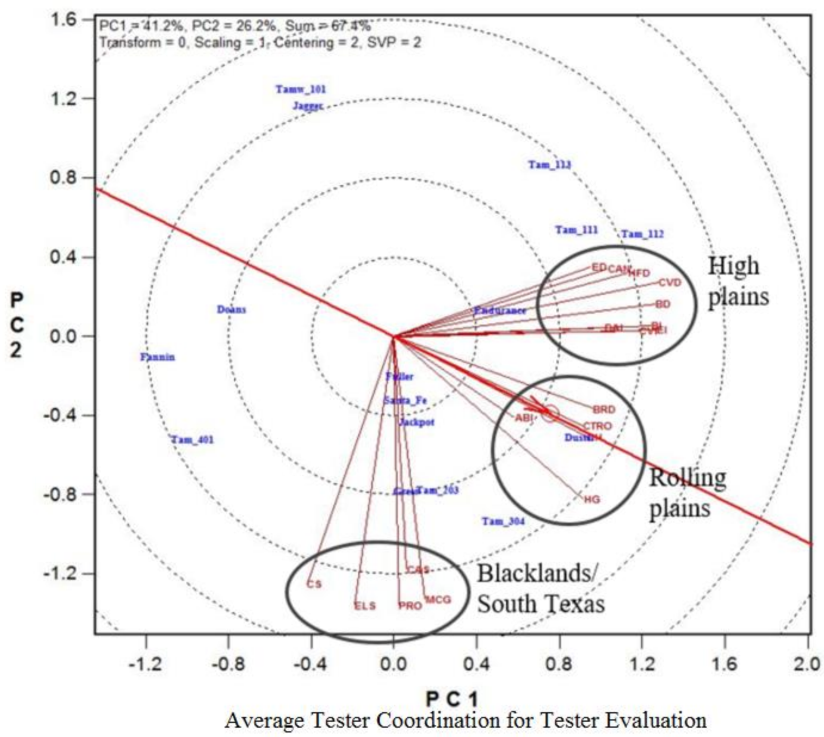

Figure 2.2 GGE biplot showing environment discrimination grouping of environments and average wheat testing location for Texas. Location Abbreviations: ABI=Abilene, BD=Bushland Dry, BI=Bushland Irrigated, BRD=Brady, CAN=Canadian, CAS=Castroville, CH=Chillicothe, CS=College Station, CVD= Clovis Dry, CVI= Clovis Irrigated, DAL=Dalhart, ED=Etter Dry, EI=Etter Irrigated, ELS=Ellis County, HFD=Hereford, HG=Hardeman, MCG=McGregor, PRO=Prosper.

The red line running through the biplot represents the average yield with the red circle lying on this line indicating the average for all locations in the analysis. A location that appears close to this point would be considered representative for the entire state of Texas. Therefore, Chillicothe and Castro County were found to be the most representative locations and would be the best for testing and selecting varieties that are generally adapted for Texas. A similar analysis previously conducted using 2004-2008 UVT data found Brady to be the best representative of all testing locations (Dr. Amir Ibrahim- Personal Communication). The change from Brady to these other two locations is most likely due to the drought conditions that were seen throughout Texas especially in 2011. Another feature of this biplot is the vector that connects each location to the center of the concentric circles which are used to approximate discriminating ability. Those with a long vector are considered very discriminating meaning that they greatly show the differences between superior and non-superior varieties. Those with very short vectors show very little variation between varieties and therefore contribute the least amount of useful information for selecting varieties. In this analysis, Abilene had the shortest vector indicating it was the least discriminating environment. Many of the locations located in the South Texas/ Blacklands and High Plains regions had long vectors and contributed the most useful information in selecting varieties. Yan (2001) describes an "ideal" location as the one that best combines discriminating ability and representativeness. The best locale was Chillicothe as it was the most discriminating testing site closest to the ideal location (Figure 2.2). The information gathered from this biplot can greatly assist in using resources efficiently. Genotype performance within a mega-environment of tightly clustered locations should be similar and therefore some can be eliminated without much loss of information. Additionally, locations that are very discriminating or representative will be retained while those that are not can be discarded.

The 'which wins where and which is best for what' biplot (Figure 2.3) shows which cultivars performed best in which environments.

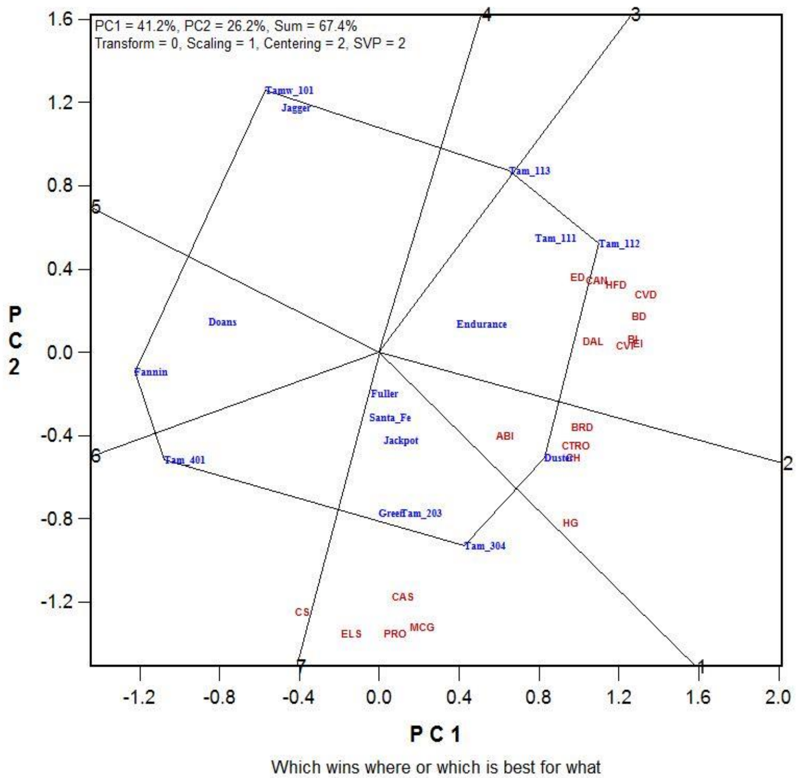

Figure 2.3 GGE biplot showing best and poorest performing cultivars for each test environment. Testing locations in red, cultivars in blue. Location Abbreviations: ABI=Abilene, BD=Bushland Dry, BI=Bushland Irrigated, BRD=Brady, CAN=Canadian, CAS=Castroville, CH=Chillicothe, CS=College Station, CVD= Clovis Dry, CVI= Clovis Irrigated, DAL=Dalhart, ED=Etter Dry, EI=Etter Irrigated, ELS=Ellis County, HFD=Hereford, HG=Hardeman, MCG=McGregor, PRO=Prosper.

In this graph, the genotypes most distant from the biplot origin are connected to create a polygon so that all other genotypes are contained within it. Perpendicular lines are then drawn from the origin to make a right angle with each side of the polygon. Genotypes that are located at the vertices of the polygon are either the best or poorest performing cultivars in one or more environments. From the biplot, TAM 112 was found to be the best performing cultivar in the cluster of locations identified as the High Plains region. TAM 111, TAM 113, and Endurance were also adapted to this region but were not as high yielding. In the cluster comprised mostly of Rolling Plains locations, Duster was found to be the top performing cultivar. TAM 304 was the best performing cultivar in the cluster of South Texas/ Blacklands locations. TAM 203, Greer, Jackpot, Santa Fe, and Fuller were also adapted to these regions but were not as high yielding. The cultivars TAMW-101, Jagger, Fannin, and TAM 401 did not perform well across a broad mega-environment. Fannin and TAM 401 were identified as the worst performers overall.

Figure 2.4 demonstrates the stability of individual genotypes across environments. In this figure, a vector is used to connect each cultivar to the average yield line. Cultivars with a short vector were stable whereas those with long vectors were not stable across environments. Additionally, cultivars that appear above the average yield line had above average yields whereas cultivars below the line had below average yields. Yields also increase moving from left to right across the graph. Duster was found to be the highest yielding and most stable cultivar across environments. Its high yielding capability could be due to its resistance to leaf rust and soil-borne mosaic virus and moderate resistance to stripe rust and powdery mildew (Oklahoma Foundation Seed Stocks, 2010). TAM 112 was the second highest yielding cultivar but was very unstable across environments. This is most likely due to leaf and stripe rust susceptibility in humid conditions such as those typically found in South Texas locations.

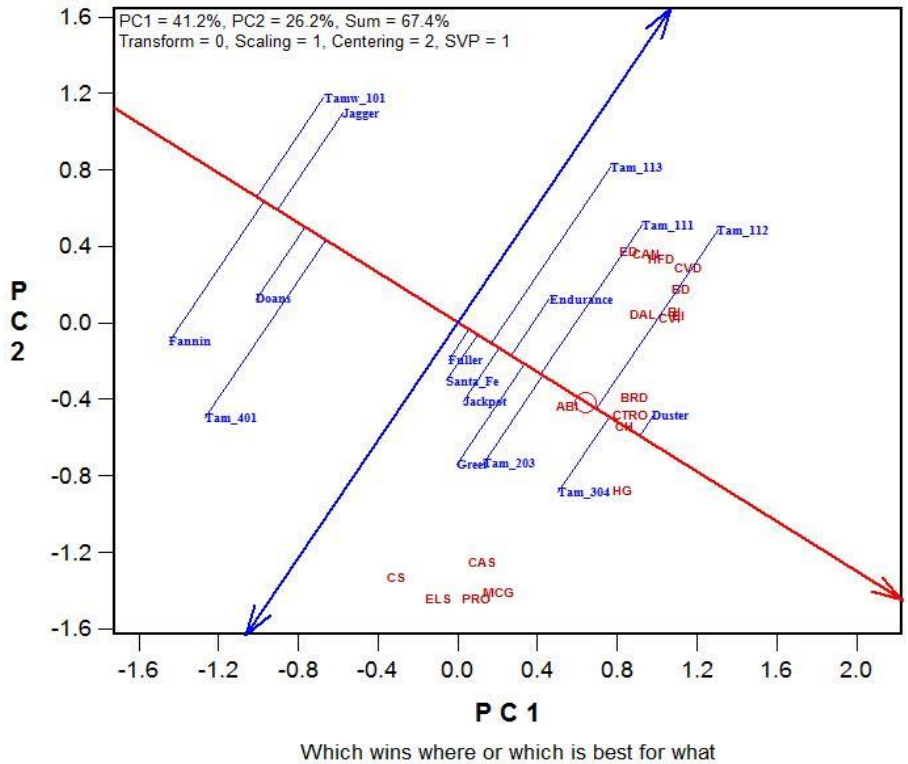

Figure 2.4 GGE biplot showing each cultivar's mean performance and stability. Location Abbreviations: ABI=Abilene, BD=Bush Dry, BI=Bush Irrigated, BRD=Brady, CAN=Canadian, CAS=Castroville, CH=Chillicothe, CS=College Station, CVD= Clovis Dry, CVI= Clovis Irrigated, DAL=Dalhart, ED=Etter Dry, EI=Etter Irrigated, ELS=Ellis County, HFD=Hereford, HG=Hardeman, MCG=McGregor, PRO=Prosper.

As seen in the previous figure, Fannin and TAM 401 were two of the lowest yielding cultivars and also unstable across environments. This study is beneficial as genotypes found to be both high yielding and stable may be used in the formation of hybrid wheat cultivars.

Conclusion

Biplot analysis is a powerful tool for plant breeders in evaluating multi-environment data. It allows for effective evaluation of the varieties and testing environments that are used in a breeding program. Based on the analysis using UVT data, mega-environments across the state of Texas were identified. Highly significant differences (P<0.0001) were found amongst environments, varieties, and environment-by-variety interaction. Biplot analysis distinguished between high and low discriminating environments and found the locations that were the best representatives of the whole state. Additionally, the best and poorest performing cultivars of each region and the stability of these cultivars were evaluated using these analyses.

CHAPTER III

EVALUATION OF TEXAS A&M WHEAT GERMPLASM FOR COMBINING ABILITY

Introduction

A key component to any breeding program is a germplasm that contains varieties with good combining ability. Through the breeding process, new varieties with good yield, biotic and abiotic tolerance, and quality traits are developed each year. In the Texas A&M wheat breeding programs, germplasm is screened for disease resistance such as rust (*Puccinia*), green bug (*Schizaphis graminum*), powdery mildew (*Erysiphaceae*), etc. and yield trials before being released as a cultivar. Typically, this is a 13 year process (Table 3.1).

Table 3.1 Wheat germplasm flow chart at Texas A&M University

Year	Trial Name	Generation
1	GH Crossing Block	
2	GH Rows	F_1
3-5	Field Plots	F_2-F_4
6	Head Rows	$F_{4:5}$
7	Observation Nurseries (SOBS)	$F_{4:6}$
8	Preliminary Yield Trials (STP)	$F_{4:7}$
9	Advanced Yield Trials (STA)	Advanced
10-12	TXE, UVT,SRPN, Increase	
13	Release	

GH= Greenhouse; SOBS= South Texas Observations; STP= South Texas Preliminary; STA= South Texas Advanced; TXE= Texas Elite; UVT= Uniform Variety Trials; SRPN= Southern Regional Performance Nursery.
Source: Dr. Amir Ibrahim, Texas A&M University- College Station

During this time, only the best performing populations, lines, or varieties will be advanced to the next stage. By the time these new selected lines are added into the South

Texas or Amarillo Observation Nursery Trials (SOBS and AOBS respectively) and other yield trials, selections on disease resistance and agronomic characteristics have already been made. Therefore it can be assumed that cultivars and breeding lines found often in the pedigrees of these newly selected lines have good general combining ability and contribute favorable genes towards new lines. Hybrid breeding programs take advantage of the yield increase observed in the progeny over the parental lines known as heterosis or hybrid vigor. It is critical to find parental combinations with good combining ability as heterosis is not observed in all crosses (Cisar and Cooper, 2002).

The main goal of this study was to evaluate Texas A&M (TAM) wheat germplasm for combining ability. In order to better understand the combining ability, it was determined how many times each cultivar or breeding line was used for developing new lines as well as the average yield contribution of a cultivar within the new lines. The cultivars identified using this method, or their progenies, may be used for hybrid wheat production.

Materials and Methods

The pedigrees of breeding lines within two data sets (observation and advanced yield trials) from both the College Station and Amarillo breeding programs were used in this study. First, the number of times a particular breeding line or cultivar was used in the formation of the new breeding lines was determined. For this, pedigree data from the 2009-2012 SOBS and AOBS trials, which contained 3420 total lines, was evaluated. The breeding lines that performed well were selected and moved to the corresponding Advanced Yield Trials (STA and AA) in 2011-2014, reducing the total number of lines to 499. Analysis was performed using Microsoft Excel and Access. The data was loaded in Excel and scrubbed to adjust any discrepancies in spelling variations, spaces, periods, etc. All symbols including brackets, parenthesis, and equals signs were eliminated so that only the forward slash (/) separating the names within the pedigrees remained. This was largely done using the ‘Find and Replace’ function. The name and pedigree data was then moved to a new worksheet and the ‘Text to Column’ function was used to break the data into separate columns. This worksheet was imported into Access and named *tInitialNameAndPedigree*. A number of queries were then used to move the data from the various pedigree columns into one pedigree field. This created and filled a table known as *01tNameAndBreedOneColumn*. Another query was used to group and count each individual pedigree breeding line or cultivar and create a table named *02tExtendedPedigreeCountFinal.* This table was then exported into Excel and the percentage of usage was calculated to compare the number of times a breeding line or cultivar had appeared to the total number of lines. Additionally, a number of queries were used as quality checks to ensure accuracy.

The average yield contribution of a breeding line or cultivar to the new lines was also assessed using the yield performance of the STA and AA line trials at eight locations (Chillicothe, Bush Dry, Bush Irrigated, Brady, McGregor, Etter Irrigated, Castroville, and Prosper). The objective was to find the average yield of each breeding line or cultivar by matching the yield of the line to each name used in its pedigree. The yield data was imported into the pedigree database from an Excel workbook to form a table named *tInitialNameYieldListing*. The name and yield fields were pulled from this table and the resulting select query was named *08NameYieldListing*. An additional query was created which formed separate entries for each name/breed combination within the pedigree. This query was named *02aUniqueNameBreedCombos*. A select query called *09NameYieldCountSum* was created using *08NameYieldListing.* This query grouped the results by name, counted the records within each name group, and summed the yield total tied to each name grouping. Select queries *02aUniqueNameBreedCombos* and *09NameYieldCountSum* were utilized to create a query which eliminated invalid breeding line or cultivar names and produced a query titled *10NameYieldBreed*. This, in turn, was used to create a select query called *11BreedYieldCountSum* which grouped by breeding line or cultivar and obtained totals by name and yield. An additional query was created using *11BreedYieldCountSum* which obtained the average yield for each breeding line or cultivar. This query was called *12AvgYieldByBreed*. A combination of *02tExtendedPedigreeCountFinal* and *12AvgYieldByBreed* was utilized to find the breeding line or cultivar name, number of times each was used, and the average yield tied to each one. This query provided the final report data.

Results and Discussion

The top contributing parents were found by comparing the results of the two data sets. In the SOBS and AOBS trials (Table 3.2 and Appendix II), TAM 112 was the most used cultivar for developing new lines appearing 505 times (14.8% of the total number of lines in the trial), which was substantially higher than the next cultivar. Jagger was present in the pedigrees of 295 lines (8.6%) representing the second most common cultivar. TAM 111 (235-6.9%), TAM 303 (214-6.3%), and TAM 203 (179- 5.2%) rounded out the top five most used cultivars.

Table 3.2 List of each variety or advanced breeding line that was used to develop new breeding lines along with the number of times each appeared in the pedigrees of a line that was part of the Observation Nurseries (SOBS and AOBS) from 2009-2012. The table also provides the corresponding percentage of the total number of lines from those years in which it appeared.

Variety or Breeding Line	Times Used	Percent
TAM 112	505	14.8%
Jagger	295	8.6%
TAM 111	235	6.9%
TAM 303	214	6.3%
TAM 203	179	5.2%
Fannin	170	5.0%
TAM 304	167	4.9%
Pecos	165	4.8%
Mason	148	4.3%
TX02U2508	143	4.2%
TAM 401	139	4.1%
TX01M5009	132	3.9%
Pastor	127	3.7%
Fuller	118	3.5%
Ogallala	117	3.4%
Cutter	100	2.9%
TX92U2317	98	2.9%
TAM 200	96	2.8%
TX01U2598	91	2.7%
JGR	90	2.6%
Bow	89	2.6%
TAM 400	88	2.6%
TX01V6008	87	2.5%
Kauz	82	2.4%
TX99A0153-1	82	2.4%
TX99M5009-28	82	2.4%
TX88V4505	80	2.3%
TX00D1390	75	2.2%
TAM 113	71	2.1%
TAM 202	69	2.0%
TX00V1131	69	2.0%
TX95D8907	69	2.0%

This table includes only the top 3% of breeding lines and varieties that were used. See Appendix II for the full listing.

Comparing this to the STA and AA trials (Table 3.3 and Appendix III), several differences can be seen. TAM 112 was still the most common cultivar appearing 92 times, representing an increase in the percentage of lines in which it appeared (18.4% of the total number of lines in this trial). TAM 111 became the second most common cultivar in this trial, present in 63 lines (12.6%). TAM 303 (46-9.2%), Jagger (43-8.6%), and Pecos (25-5.0%)/TAM 304 (25-5.0%) rounded out the top six most utilized cultivars.

Table 3.3 List of each variety or advanced breeding line that was used to develop new lines along with the number of times each appears in pedigrees of a line that was part of the Advanced Yield Trials (STA and AA) from 2011-2014. The table also provides the corresponding percentage of the total number of lines from those years in which it appeared.

Variety or Breeding Line	Times Used	Percent
TAM 112	92	18.4%
TAM 111	63	12.6%
TAM 303	46	9.2%
Jagger	43	8.6%
Pecos	25	5.0%
TAM 304	25	5.0%
TAM 401	23	4.6%
Mason	20	4.0%
TX02U2508	20	4.0%
TAM 203	19	3.8%
TX92U2317	19	3.8%
TX99A0153-1	19	3.8%
Fannin	18	3.6%
TX01V6008	18	3.6%
TAM 113	17	3.4%
TX95D8907	17	3.4%
TX96D1073	16	3.2%
Trego	15	3.0%
TAM 202	14	2.8%
TX99A0155	14	2.8%
TX00D1390	13	2.6%
Cutter	12	2.4%
TAM 200	11	2.2%

Table 3.3 Continued

Variety or Breeding Line	Times Used	Percent
TX00V1131	11	2.2%
TX03V71103	11	2.2%
TX99U8618	11	2.2%
Pastor	10	2.0%
CO960293	10	2.0%
KS005F5	10	2.0%
TX02D6112	10	2.0%
Weebill	10	2.0%

This table includes only the top 7% of breeding lines and varieties that were used. See Appendix III for the full listing.

Cultivars or breeding lines that show exceptional performance in regards to yield, disease resistance, or quality are targeted in the crossing block to combine with other top performers in hopes of developing superior varieties with favorable traits from both parents. The cultivars that appear at the top of these lists are known for their performance and the fact that they are common within the pedigrees of advanced lines indicate that they consistently pass on favorable genes to their progeny and have good general combining ability. It is not surprising that TAM 112 has been used extensively in developing new lines. It has very high grain and forage yield and is widely adapted to grow in the High Plains of Texas and many other states in the Southern Great Plains (Texas Foundation Seed Service, 2015). TAM 112 also shows resistance to greenbug (same resistance genes as those in TAM 110) and has good milling and baking characteristics (Rudd et al., 2014). Similarly, TAM 111 is also known for its high yielding ability as well as having excellent drought resistance (Larza et al., 2004). The grain quality is generally superior to other popular varieties released by Texas A&M AgriLife Research as well. TAM 303 is best suited for the Texas Blacklands and although it is not as high yielding as TAM 111 or TAM 112, it is highly resistant to leaf rust and many other foliar diseases (Texas Foundation Seed Service, 2015). Jagger, released in 1994, had improved yield, milling, and baking qualities over previous cultivars and was the most widely planted cultivar in Kansas and Oklahoma for a number of years beginning in the late 1990’s (Ohlemeier, 1999).

Analyses of the STA and AA yield performance data revealed the varieties and breeding lines which had the highest average yields (Table 3.4 and Appendix III). The top five highest yielding were advanced breeding lines that were not released as varieties. Although they contribute to producing new high yielding lines, and were most likely high yield varieties themselves, they were not released due, most likely, to disease susceptibility or quality concerns.

Table 3.4 List of each variety or advanced breeding line that was used to develop new lines along with the number of times each appears in pedigrees of a line that was part of the Advanced Yield Trials (STA and AA) from 2011-2014. The table also shows the corresponding percentage of the total number of lines from those years in which it appeared. Sorted to show the mean yield of the progeny of each variety or breeding line from highest to lowest.

Variety or Breeding Line	Times Used	Percent	Kilograms/ Hectare (kg/ha)
TX92U2317	19	3.8%	3518.03
TX03V71103	11	2.2%	3511.81
TX95D8907	17	3.4%	3498.57
TX99A0153-1	19	3.8%	3474.57
TX00D1390	13	2.6%	3473.60
Pastor	10	2.0%	3400.37
CO960293	10	2.0%	3387.39
TAM 200	11	2.2%	3385.24
KS005F5	10	2.0%	3345.83
Weebill	10	2.0%	3338.08
Kauz	12	2.4%	3314.87
TAM 113	17	3.4%	3301.52
FANNIN	18	3.6%	3277.35
Pecos	25	5.0%	3274.82

Table 3.4 Continued

Variety or Breeding Line	Times Used	Percent	Kilograms/ Hectare (kg/ha)
Ogallala	21	4.2%	3262.08
TAM 203	19	3.8%	3261.23
TX02D6112	10	2.0%	3236.75
TX02U2508	20	4.0%	3211.57
TX01V6008	18	3.6%	3198.07
Trego	15	3.0%	3174.37
TAM 401	23	4.6%	3135.05
Jagger	43	8.6%	3086.91
Mason	20	4.0%	3044.53
TAM 304	25	5.0%	3020.58
TX99A0155	14	2.8%	2998.22
TAM 111	63	12.6%	2981.67
Cutter	12	2.4%	2946.18
TAM 112	92	18.4%	2939.77
TAM 303	46	9.2%	2912.04
TX00V1131	11	2.2%	2802.53
TX96D1073	16	3.2%	2801.28
TX99U8618	11	2.2%	2435.16

This table includes the varieties and breeding lines that were most commonly used as seen in Table 3.3, but is sorted based on average yield of the lines. The full listing can be seen in Appendix III.

Conclusion

High performing cultivars and advanced breeding lines with good general combining ability are essential for hybrid wheat production. Heterosis may not occur without lines that have good combining ability. A model for evaluating the pedigrees of lines within trials was developed which can be used in future studies. This evaluation found several cultivars and breeding lines that were present in many of the SOBS/AOBS and STA/AA line trial pedigrees. This study combined with floral characteristic data will assist in determining the best candidates for the TAMU hybrid wheat breeding program.

CHAPTER IV

ESTIMATING HETEROSIS AND COMBINING ABILITY AMONG A SELECTED SET OF TAM WHEAT VARIETIES

Introduction

Although the effect of heterosis is generally more expressed in cross-pollinating crops than self-pollinated ones (Gallais, 1988), many experiments have been conducted to determine the heterosis that occurs in a number of self-pollinating crops including wheat. Heterosis observations in wheat began as early as 1919 (Freeman, 1919) and interest in the possibility of commercially produced hybrid wheat sparked a surge of research in the 1960s. With improved methods of creating male sterility in wheat such as CMS and CHAs over the past 60 years, potential gains in yield due to heterosis in wheat has become the focus of much research. It has been noted that not all parental combinations will result in heterosis; however, many published reports confirm that heterosis does occur when the correct combinations are made (Akinci, 2009). It has been suggested that the most effective heterosis occurs between parents with a wide genetic divergence (Coors and Pandey, 1999). Support for this statement was made by Duvick (1999) who found that heterosis can reach up to 30% as a result of crosses between classes of wheat such as hard and soft winter wheat cultivars. SNP markers have been used to estimate genetic distances in wheat and other crops (Ren et al., 2013; Singh et al., 2013). As knowledge of molecular genetics and technology used for genetic mapping rapidly advances, these theories will be more easily tested.

Diallel analysis is a common method for estimating heterosis, GCA, and SCA. Variability found through diallel analysis has generally been attributed to GCA (Bitzer et al., 1982). Although estimates of high parent heterosis using this analysis has exceeded 100%

(Fonseca and Patterson, 1968), it is believed to be much lower. Longin (2012) concluded the average heterosis to be around 10% in grain yield. Studies on a 7x7 bread wheat diallel cross by Borghi and Perenzin (1994) revealed a standard heterosis of only 3.3%, but also found one hybrid that was short and had superior bread making quality that signified a 30% higher selling price. Borghi and Perenzin concluded that the first generation of hybrids would therefore be only slightly superior in yield potential but would have other desirable traits like bread-making quality. In conducting an eight-parent diallel cross of soft red winter wheat, Bitzer et al. (1982) found mid-parent heterosis values of 30% for low × low yielding parental crosses, 25% for low × high crosses, and 19% for high × high crosses. Estimates of GCA found that three of the four low yielding parents had negative effects and three of the four high yielding parents had positive effects (Bitzer et al., 1982). They concluded that negative effects were more often associated with low yielding parents and that successful hybrids will most likely occur through high × high crosses due to GCA effects in wheat (Bitzer et al., 1982). A six-parent diallel durum wheat cross found high parent heterosis up to 23.92% (Akinci, 2009). These experiments indicate that hybrid wheat has the potential to increase yield and improve other characteristics such as end-use quality.

In this study, F_1 hybrids from an 8×8 wheat diallel cross was used to estimate heterosis, GCA, and SCA effects for yield and yield components. The results of this experiment will be used in conjugation with ongoing research on floral characteristics to determine the best candidates for the Texas A&M hybrid wheat breeding program.

Materials and Methods

Plant Material and Experimental Design

Eight hard red winter wheat lines from the TAM germplasm (Table 4.1) were entered into a half diallel mating design.

Table 4.1 TAM hard red winter wheat varieties and corresponding pedigree that were entered into a half-diallel mating design

Variety	Pedigree
TAM 111	TAM 107//TX78V3620/CTK78/3/TX87V1233
TAM 112	U1254-7-9-2-1/TXGH10440
TAM 113	TX90V6313//TX94V3724(TAM-200 BC41254-1-8-1-1/TX86V1405
TAM 305	TX97V3006/TX98V6239
TAM 401	MASON/JAGGER
TX11D3108	TX03V73097/TX99M5009-28
Sturdy 2K	Selection from Sturdy (Citr 13684=Sinvalocho / Wichita // Hope / Cheyenne /3/2* Wichita /4/ Seu Seun 27) released in 1966
TX10D2230	NW01L2019/TX96D1073//TX01D3215

Source of seed and pedigrees: Dr. Amir M.H. Ibrahim, Texas A&M University- College Station

At least twelve seeds of each cross were germinated in petri dishes and vernalized for six weeks in cool storage (3°C). Although only nine seeds were used for planting, extras were added in case any did not germinate or survive through vernalization. These F_1 seeds were then planted at a density of three seeds (when available) per six inch pot and laid out in a complete randomized design (CRD) with three replications in a growth chamber. The growth chamber was set for optimum wheat growing conditions (a 14 hour day length, 25°C day temperature, and 18°C night temperature). Miracle-Gro All Purpose Plant Food was applied a week after planting followed by the addition of Miracle-Gro Shake’n Feed continuous release fertilizer a week later. Similar methods were used for growing the F_2 generation. There were 36 pots per replication for a total of 108 pots as seen in the calculation below:

[(8 parental lines)+ (28 F_1 lines)] x (3 reps) = 108 total pots.

Phenotypic Evaluation

Heading date was recorded according to the Julian Date Calendar when the head of the wheat plant had completely emerged from the boot. The average height of the plants were taken with a meter stick from the soil surface to the tip of the wheat spike excluding the awns. A count of the number of tillers, wheat heads, and seeds was taken and yield (in grams) was measured. These measurements were taken on a per pot basis.

Statistical Analysis

Mid and high-parent heterosis was determined from the yield data using the following formulae:

Mid-parent heterosis %= 100*(F1-MP)/MP where MP= (P1+P2)/2

High-parent heterosis %= 100*(F1-HP)/HP where HP is the higher yielding parent

Diallel SAS (Zhang and Kang, 1997) was used to estimate GCA and SCA effects of yield. ANOVA for yield and its components were performed using SAS v9.3 (SAS inc., 2008). Least significant differences (LSD) was calculated for yield per pot for a comparison between each entry. The formula $t_{\alpha/2}$*sqrt(2*MSE/r) was used to compare entries with equal number of replications while the formula $t_{\alpha/2}$*sqrt((MSE^2/r1)+(MSE/r2)) was used to compare entries with an unequal number of replications (due to some pots not having any yield).

Results and Discussion

An ANOVA for grain yield per pot of the F_1 generation revealed highly significant differences ($P<0.0005$) among entries (Table 4.2) and had a coefficient of variation (CV) of 28.47%. To better understand the differences between individual entries, a calculation of least significant differences (LSD) was performed (Appendix V) and 345 of the 630 total comparisons were found to be significant (P<0.05). Significant to highly significant differences were found for each yield component (Table 4.2), which included heading date (P<0.005), heads per pot (P<0.0005), plant height (P<0.0005), seeds per head (P<0.0005), and seed weight (P<0.05).

Table 4.2 Combined ANOVA for F_1 yield and yield components mean squares.

	DF	GY/P	DH	HP	Height	S/H	SW
Treatment	37	7.19	5.88	43.67	18.03	125.64	0.00>
Error	64-70	1.16	2.76	6.07	5.97	45.09	0.00>
Significance		***	**	***	***	***	*
CV (%)		28.47	10.37	38.9	8.95	26.68	24.82

DF= Degree of Freedom, GY/P= Grain Yield per Pot, DH= Days to Heading, HP=Heads per Pot, S/H= Seeds per Head, SW= Seed Weight, *=Significance to p<0.05, **=Significant to p<0.005, ***=Significant to p<0.0005

The mid and high-parent heterosis was calculated based on grain yield per plant due to unequal number of plants per pot. TAM 113 and TAM 305 were the highest yielding parental plants (Table 4.3) producing an average of 2.03 grams per plant. The cross ‘TAM 111’ × ‘TX10D2230’ had the greatest high-parent heterosis at 177.78%.

Table 4.3 The mean grain yield per plant and mid and high-parent heterosis of the parents and their F_1’s in an 8x8 half-diallel cross that was grown in a growth chamber at College Station, TX during 2014.

Parents and F_1’s	Yield/Plant (g)	Mid-Parent Heterosis (%)	High-Parent Heterosis (%)
TAM 113 x Sturdy 2K	3.84	182.45%	88.85%
TAM 401 x TX11D3108	2.01	105.67%	39.45%
TAM 113 x TAM 305	1.99	-1.98%	-2.19%
TAM 112 x TAM 113	1.86	38.82%	-8.74%
TAM 113 x TX10D2230	1.85	55.90%	-9.02%
TAM 111 x TAM 305	1.74	43.87%	-13.85%
TAM 112 x TX11D3108	1.71	196.48%	167.36%
TAM 401 x Sturdy 2K	1.70	59.61%	17.69%

Table 4.3 Continued

Parents and F_1's	Yield/Plant (g)	Mid-Parent Heterosis (%)	High-Parent Heterosis (%)
TAM 305 x TAM 401	1.66	-4.16%	-17.90%
TAM 112 x TX10D2230	1.66	238.78%	159.38%
TAM 113 x TX11D3108	1.64	29.10%	-19.13%
TAM 111 x TAM 401	1.62	75.90%	12.31%
TAM 113 x TAM 401	1.62	-6.71%	-20.22%
TAM 305 x TX10D2230	1.60	35.31%	-20.99%
TAM 401 x TX10D2230	1.60	79.33%	10.77%
TAM 112 x TAM 305	1.59	19.24%	-21.54%
TAM 111 x TAM 112	1.53	194.87%	139.58%
TX11D3108 x TX10D2230	1.33	210.20%	157.64%
TAM 111 x TAM 113	1.27	4.50%	-37.47%
TAM 111 x TX10D2230	1.11	200.30%	177.78%
TX11D3108 x Sturdy 2K	1.10	83.33%	60.42%
TAM 305 x Sturdy 2K	1.10	-18.84%	-45.68%
TAM 305 x TX11D3108	0.93	-26.49%	-53.91%
TAM 112 x Sturdy 2K	0.78	18.18%	14.24%
TAM 111 x TX11D3108	0.70	53.13%	36.11%
Sturdy 2K x TX10D2230	0.55	7.24%	-19.79%
TAM 111 x Sturdy 2K	0.40	-26.32%	-41.67%
TAM 113	2.03		
TAM 305	2.03		
TAM 401	1.44		
Sturdy 2k	0.69		
TAM 112	0.64		
TX11D3108	0.51		
TAM 111	0.40		
TX10D2230	0.34		

High-parent heterosis up to 200% have been reported in other studies (Cisar and Cooper, 2002; Fonseca and Patterson, 1968), but the high values (five crosses over 100% high-parent heterosis) seen in this study can be attributed to several factors. The first being that these plants were grown in ideal conditions with limited stress leading to higher yields than would be expected in field conditions. Another factor is the uneven and poor performance seen by five of the eight of the parental varieties. TAM 111 and TAM 112 are known for being among the highest yielding cultivars of the TAM germplasm and would be expected to be high yielding when grown in growth chamber conditions with limited stress. However, in the F1 generation, TAM 113 and TAM 305 had yields about four times that of TAM 111 and TAM 112 indicating that these varieties yielded poorly based on knowledge of how these cultivars typically perform. Although there is not a clear explanation for why this occurred, it helps explain why such large heterosis values were obtained. The yields of the parents are used when determining mid and high-parent heterosis and therefore if the parents did not perform well it can lead to an overestimation of the heterosis value. A final factor is that although these calculations were made based on yield per plant rather than yield per pot, it still does not account for the advantage seen by plants growing with more space (which encourages tillering) over those grown with less space. Heterosis is generally exaggerated under spaced planting conditions such as in the case of pots in a growth chamber as well. The only F_1 hybrid that out-yielded the two parent cultivars with the highest yield was the cross 'TAM 113' × 'Sturdy 2K', which yielded 3.84 grams per plant and was found to have a high-parent heterosis of 88.85%. TAM 113 was found to be a parent in four of the top five highest yielding F_1's, indicating that it had good GCA.

The estimates of GCA effects (Table 4.4) for grain yield per pot found TAM 113, TAM 305, and TAM 401 to be highly significant (P<0.0005) for positive effects while TAM 111, Sturdy 2K, and TX10D2230 were found to be highly significant (P<0.005) for negative effects.

Table 4.4 Estimates of GCA effects for grain yield per pot of the F_1 progeny grown in a growth chamber at College Station, TX during 2014

Parent	Parameter	Estimate
TAM 111	G1	-3.36**
TAM 112	G2	0.89^{NS}
TAM 113	G3	5.39***
TAM 305	G4	4.32***
TAM 401	G5	4.46***
TX11D3108	G6	-1.13^{NS}
Sturdy 2K	G7	-5.34***
TX10D2230	G8	-5.22***

NS=Not Significant, **=Significant to p<0.005, ***=Significant to p<0.0005

The effects of TAM 112 and TX11D2230 were not found to be significant. The estimates of SCA effects (Table 4.5) for grain yield found eight of the F_1 progeny to be significant (P<.05) for positive effects and five to be significant for negative effects. The SCA effect with the highest value was the cross 'TAM 113' x 'Sturdy 2K', which was the highest yielding F_1 in this experiment. The remaining fifteen F_1 progeny were found to be not significant for SCA effects.

Table 4.5 Estimates of SCA effects for grain yield per pot of the F_1 progeny grown in a growth chamber in College Station, TX during 2014

Number	Variety
1	TAM 111
2	TAM 112
3	TAM 113
4	TAM 305
5	TAM 401
6	TX11D3108
7	Sturdy 2K
8	TX10D2230

Table 4.5 Continued

Parameter	Estimate
S11	-2.93**
S12	2.52*
S13	-2.02*
S14	2.44*
S15	1.73^{NS}
S16	-1.25^{NS}
S17	-2.57*
S18	3.53***
S22	-4.30***
S23	1.14^{NS}
S24	0.09^{NS}
S25	0.70^{NS}
S26	2.69*
S27	-2.22*
S28	2.90***
S33	0.45^{NS}
S34	0.64^{NS}
S35	-1.39^{NS}
S36	0.73^{NS}
S37	4.86***
S38	-3.08**
S44	0.01^{NS}
S45	-1.78^{NS}
S46	-2.73*
S47	-0.99^{NS}
S48	1.43^{NS}
S55	-1.80^{NS}
S57	0.82^{NS}
S58	2.06*
S66	-3.28***
S67	1.61^{NS}
S68	3.50***
S77	0.05^{NS}
S78	-0.99^{NS}
S88	-4.67***

NS=Not Significant, **=Significant to p<0.005, ***=Significant to p<0.0005

An ANOVA for grain yield per pot (Table 4.6) using SAS (Appendix VI) of the F_2 generation found significant differences ($P<0.05$) between entries and had a CV of 24.52%.

Table 4.6 ANOVA for grain yield per pot of the F_2 generation mean squares

Source	DF	Sum of Squares	Mean Square	F Value
Treatment	35	33.68	0.96	1.77*
Error	72	39. 17	0.54	
Corrected Total	107	72.85		

*=Significance to $p<0.05$

The performance the parents was found to be more consistent than what was seen in the F_1's and mid and high-parent heterosis (Table 4.7) was calculated based on yield per plant as was done in the F_1 generation. Several of the F_2's outperformed the highest yielding parental varieties with the cross 'TAM 113' x 'TX11D3108' having the highest yield averaging 1.42 grams per plant and had a high parent heterosis of 36.39%. TAM 113 was found to be a parent in two of the three highest yielding F_2's, reaffirming the belief that it has good GCA.

Table 4.7 The mean grain yield per plant and mid and high-parent heterosis of the parents and their F_2's in an 8x8 half-diallel cross that was grown in a growth chamber in College Station, TX during 2015.

Parents and F_2's	Yield/Plant (g)	Mid-Parent Heterosis (%)	High-Parent Heterosis (%)
TAM 113 x TX11D3108	1.42	42.24%	36.39%
TAM 111 x TAM 112	1.31	45.60%	25.99%
TAM 113 x TAM 401	1.25	28.65%	20.28%
TX11D3108 x Sturdy 2K	1.23	17.29%	7.80%
TAM 111 x Sturdy 2K	1.22	12.16%	7.41%
TAM 112 x TAM 305	1.22	59.36%	59.24%
TAM 113 x TX10D2230	1.15	5.33%	0.85%
TAM 113 x Sturdy 2K	1.14	4.43%	-0.10%
TAM 112 x TX10D2230	1.12	17.43%	-1.95%

Table 4.7 Continued

Parents and F_2's	Yield/Plant (g)	Mid-Parent Heterosis (%)	High-Parent Heterosis (%)
TAM 111 x TAM 305	1.11	22.88%	6.39%
TAM 113 x TAM 305	1.08	19.58%	3.63%
TAM 111 x TAM 401	1.07	9.92%	2.66%
TAM 112 x TX11D3108	1.05	10.05%	9.53%
TAM 401 x Sturdy 2K	1.04	1.79%	-8.67%
TAM 111 x TX11D3108	1.04	4.06%	-0.32%
TX11D3108 x TX10D2230	1.04	-0.85%	-8.79%
TAM 305 x TX11D3108	1.02	19.07%	7.09%
TAM 401 x TX10D2230	0.99	-2.77%	-12.70%
TAM 305 x TX10D2230	0.92	-2.86%	-18.85%
TAM 305 x TAM 401	0.91	8.92%	0.37%
TAM 112 x TAM 113	0.90	0.06%	-13.34%
TAM 401 x TX11D3108	0.88	-5.67%	-8.14%
TAM 111 x TX10D2230	0.85	-21.75%	-25.00%
TAM 112 x Sturdy 2K	0.81	-14.37%	-28.56%
Sturdy 2K x TX10D2230	0.73	-36.10%	-36.16%
TAM 111 x TAM 113	0.70	-32.52%	-32.59%
TAM 305 x Sturdy 2K	0.69	-27.96%	-39.86%
TAM 112 x TAM 401	0.58	-30.18%	-35.71%
Sturdy 2K	1.14		
TX10D2230	1.14		
TAM 111	1.04		
TAM 113	1.04		
TX11D3108	0.96		
TAM 305	0.76		
TAM 112	0.76		

Estimates of GCA effects for grain yield in the F_2 generation (Table 4.8) found none of the parents to be significant ($P<0.05$).

Table 4.8 Estimates of GCA effects for grain yield per pot of the F_2 progeny grown in a growth chamber in College Station, TX during 2015

Parent	Parameter	Estimate
TAM 111	G1	0.03^{NS}
TAM 112	G2	-0.04^{NS}
TAM 113	G3	0.07^{NS}
TAM 305	G4	-0.05^{NS}

Table 4.8 Continued

Parent	Parameter	Estimate
TAM 401	G5	-0.06^{NS}
TX11D3108	G6	0.07^{NS}
Sturdy 2K	G7	-0.01^{NS}
TX10D2230	G8	-0.02^{NS}

NS= Not significant at 5% level of significant

Only three of the crosses were found to be significant ($P<0.05$) for positive SCA effects for grain yield and four were found to be significant ($P<0.05$) for negative SCA effects. This is not surprising as studies (Bitzer, 1982) have found heterosis levels in the F_2 generation not to be significant over the parental varieties due to the 50% decrease in heterosis from the F_1 generation to the F_2 generation.

Table 4.9 Estimates of SCA effects for grain yield per pot of the F_2 progeny grown in a growth chamber in College Station, TX during 2015

Number	Variety
1	TAM 111
2	TAM 112
3	TAM 113
4	TAM 305
5	TAM 401
6	TX11D3108
7	Sturdy 2K
8	TX10D2230
Parameter	**Estimate**
S11	-0.04*
S12	0.31***
S13	-0.42^{NS}
S14	0.11^{NS}
S15	0.08^{NS}
S16	-0.07^{NS}
S17	0.19^{NS}
S18	-0.14^{NS}
S22	-0.17^{NS}

Table 4.9 Continued

Parameter	Estimate
S23	-0.14^{NS}
S24	0.29*
S25	-0.33**
S26	0.01^{NS}
S27	0.14^{NS}
S28	0.33^{NS}
S33	-0.12^{NS}
S34	0.04^{NS}
S35	0.22^{NS}
S36	0.27*
S37	0.06^{NS}
S38	0.20^{NS}
S44	-0.15^{NS}
S45	0.00^{NS}
S46	0.01^{NS}
S47	-0.27*
S48	0.13^{NS}
S55	0.01^{NS}
S57	0.10^{NS}
S58	0.05^{NS}
S66	-0.19^{NS}
S67	0.16^{NS}
S68	0.17^{NS}
S77	0.15^{NS}
S78	-0.40*
S88	-0.34^{NS}

NS=Not Significant, **=Significant to p<0.005, ***=Significant to p<0.0005

Conclusion

Significant differences for yield and all yield components were found in the F_1 hybrids from an 8×8 half-diallel. High-parent heterosis estimates exceeded 175%, which was due to several factors including poor performance of several of the parental lines. Estimates of GCA for plant yield revealed that three of the eight parents were highly significant

($P<0.0005$) for positive effects and three were highly significant ($P<0.005$) for negative effects. Eight of the F_1 progeny had highly significant positive effects for SCA, while five had highly significant negative effects. Although heterosis decreases by 50% in the F_2 generation, this generation can be used, as a proxy, to estimate F_1 heterosis (Bailey et al., 1980). High-parent heterosis values were found up to 59.24% in the F_2 generation. None of the parents were found to be significant ($P<0.05$) for GCA effects for grain yield while three crosses were found to be significant ($P<0.05$) for positive SCA effects and four were found to be significant for negative SCA effects.

CHAPTER V

SUMMARY

The success of hybrid wheat is dependent on the ability to create hybrid cultivars that can outperform current conventional cultivars in grain yield production, disease resistance, or end-use quality. Research into hybrid wheat began almost 100 years ago and yet there is still no production in the United States and very little production worldwide. However, due to advances in technology that improve the efficiency of selecting and testing cultivars, hybrid wheat may be available by the end of the decade.

Analyses of multi-environment data for wheat yield using biplots found genotypes and environments that will be useful in the TAM hybrid wheat breeding program. Environments that are highly discriminatory and representative of the entire state have been identified and will be used for testing potential hybrid cultivars. Other environments that are consistently high yielding were identified as being suitable for maximal hybrid seed production. High yielding and stable cultivars were also identified which may be used in the hybrid wheat crossing block depending on their floral characteristics.

Analysis of the SOBS/AOBS and STA/AA line trials assisted in gaining a better understanding of the TAM wheat germplasm. Genotypes that commonly appear in the pedigrees of new lines were identified and the average yield contribution to these new lines was also determined. The method used for evaluating pedigrees of lines in this study can be utilized in future research. The genotypes identified as potentially having good GCA may be implemented into a hybrid wheat breeding program directly, by being used as a parent for hybrid cultivars, or indirectly, by being used to create other cultivars which will then be implemented in hybrid wheat production.

The 8x8 half-diallel cross allowed for an estimation of heterosis among a selected set of TAM wheat varieties. Statistical analysis using ANOVA found highly significant differences for grain yield and yield components among the F_1 progeny. High levels of heterosis were also observed. The GCA and SCA estimates identified the lines that had positive and negative effects on grain yield. The results of this study gave an initial estimation of the potential heterosis that can be expected from the TAM wheat germplasm.

The TAM hybrid wheat program possesses the attributes needed for successful hybrid wheat cultivar production. This includes diverse environments for testing potential hybrid cultivars as well as high yielding genotypes with good combining ability. This study, along with work being done by fellow researchers, brings the TAM wheat breeding program into the race to release a hybrid wheat cultivar.

REFERENCES

Agriculture Marketing Resource Center. 2012. Wheat. Available at: Date visited: August 31, 2015.http://www.agmrc.org/commodities__products/grains__oilseeds/wheat/.

Allen-Stevens, T. 2012. Bigger, bolder, stronger? Crop Production Magazine. Date visited: August 15, 2015Available from: http://www.ble-hybride.com/anglais/information-and-news/press-review/bigger-bolder-stronger-cpm-aout-2012-669.aspx. Date visited: August 15, 2015

Aune, D. 2015. Agriculture analysis leads to vital economic decisions. Available at: http://www.sas.com/en_us/customers/usda-nass.html. Date visited: September 7, 2015.

Baenziger, Stephen. Professor- University of Nebraska- Department of Agronomy and Horticulture.

Bailey, Jr., T. B., C. O. Qualset, D. F. Cox. 1980. Predicting Heterosis in Wheat. Crop Science 20:339-342.

Becker, H.C., and J. Leon. 1988. Stability analysis in plant breeding. Plant Breeding 101: 1-23.

BeiRu, H., H. YinGang, S. XiYue, M. LingJian, L. HongBing, D. PuHui, Y. Ling. 2008. Preliminary study of fertility conversion in the thermos-sensitive male sterile wheat line YM3314 with the chromosome segments of *Triticum macha*. Journal of Triticeae Crops 28(2): 206-209.

Bitzer, M.J., F.L. Peterson, W.E. Nyquist. 1982. Hybrid vigor and combining ability in a high-low yielding, eight-paren diallel cross of soft red winter wheat. Crop Science 22: 1126-1129.

Borghi, B., M. Perenzin. 1994. Diallel analysis to predict heterosis and combining ability for grain yield, yield components and bread-making quality in bread wheat (*T. aestivum*). Theoretical Applied Genetics 89: 975-981.

Bradu, D., and K.R. Gabriel. 1978. The biplot as a diagnostic tool for models of two-way tables. Technometrics 20: 47-68.

Braun, H.J., G. Atlin, T. Payne. 2010. Multi-location testing as a tool to identify plant response to global climate change. In: M. P. Reynolds (Ed.), Climate Change and Crop Production, CABI Climate Change Series, Surrey, UK. Pp.115-138.

Briggle, L.W. 1963. Heterosis in Wheat- a review. Crop Science 3: 407-411.

Castillo, A., S. Atienza, A. Martin. 2014. Fertility of CMS wheat is restored by two Rf loci located on a recombined acrocentric chromosome. Journal of Experimental Botany 10.1093

Chantret, N., J. Salse, F. Sabot, S. Rahman, A. Bellec, B. Laubin, I. Dubois, C. Dossat, P. Sourdille, P. Joudrier, M. Gautier, L. Cattolico, M. Beckert, S. Aubourg, J. Weissenbach, M. Caboche, M. Bernard, P. Leroy, B. Chalhoub. 2005. Molecular basis of evolutionary events that shaped the hardness locus in diploid and polyploidy wheat species. Plant Cell 17(4): 1033-1045.

Chopra, V.L., S.K. Jain, M.S. Swaminathan. 1960. Indian J. Genet., 20: 188-199

Cisar, G., and D.B. Cooper. 2002. Hybrid Wheat. In: Bread wheat (eds Curtis B.C., Rajaram S, Gomez Macpherson H). Date visited: September 1, 2015 Available from http://www.fao.org/DOCREP/006/Y4011E/Y4011E00.HTM.

Coors, J.G, and S. Pandey. 1999. The genetics and exploitation of heterosis in crops. ASA, CSSA, and SSSA, Madison.

De Vries, A. 1970. Flowering Biology of Wheat, Particularly in View of Hybrid Seed Production- A review. Euphytica 20: 152-170.

Driscoll, C.J. 1972. XYZ system of producing hybrid wheat. Crop Science 12: 516-517.

Driscoll, C.J. 1985. Modified XYZ system of producing hybrid wheat. Crop Science 25: 1115-1116.

Dubcovsky, J., J. Dvorak. Genome plasticity a key factor in the success of polyploidy wheat under domestication. *Science* 316 (2007): 1862-1866.

Duvick, D.N. 1999. Commercial strategies for exploitation of heterosis. In: James G. Coors and Shivaji Pandey, eds. Genetics and exploitation of heterosis in crops. American Soiciety of Agronomy, Madison, Wisconsin: 295-304.

Edwards, I. 2001. Origin of cultivated wheat. Bonjean AP, Angus WJ, eds. The world wheat book: a history of wheat breeding. Paris, France: Lavoisier Publishing, 1019-1045.

Edwards, I., G. Dorlencourt. 1994. Hyrid wheat- current status and future role in European wheat production. Melhoramento 33: 87-104.

Eversole, K., C. Feuillet, K. Mayer, and J. Rogers. Slicing the wheat genome. July 2014. Science Magazine 345.6194: 285-287.

Feldman, M. 1995. Wheats. In: Smartt J, Simmonds NW, eds. Evolution of crop plants. Harlow, UK: Longman Scientific and Technical, 185-192.

Feldman, M. 2001. Origin of cultivated wheat. Bonjean AP, Angus WJ, eds. The world wheat book: a history of wheat breeding. Paris, France: Lavoisier Publishing, 3-56.

Feuillet, Catherine., P. Langridge, and R. Waugh. January 2008. Cereal breeding takes a walk on the wild side. Trends in Genetics 24(1): 24-32.

Fischer, S., J. Mohring, C.C. Schon, H-P. Piepho, D. Klein, W. Schipprack, H.F. Utz, A. Melchinger, J.C. Reif. 2008. Trends in genetic variance components during 30 years of hybrid maize breeding at the University of Hohenheim. Plant Breeding 127(5): 446-451.

Fonseca, S., and F. Patterson. 1968. Hybrid vigor in a seven-parent diallel cross in common winter wheat (*Triticum aestivum* L.). Crop Science 8: 85-88.

Food and Agricultural Organization of the United Nations. 2015. FAO Cereal Supply and Demand Brief. Date visited: August 25, 2015. Available from http://www.fao.org/worldfoodsituation/csdb/en/.

Foster, J. 2011. Hybrid Wheat. Saaten-Union/Claude Reynier Video Films. Available at: https://vimeo.com/58297945. Date visited: August 30. 2015

Gabriel, K.R. 1971. The biplot graphic display of matrices with application to principle component analysis. Biometrka 58: 453-467

Gowda, M., C.F.H. Longin, V. Lein, J.C. Reif. 2012. Relevance of specific versus general combining ability in winter wheat. Crop Science 52: 2494-2500.

Griekspoor, P.J. 2013. Company targets 2020 for hybrid wheat. Farm Futures Magazine. Available at http://farmfutures.com/story-company-targets-2020-hybrid-wheat-18-100119. Date visited: August 31, 2015

Haider, N. March 2013. The origin of the B-genome of bread wheat (Triticum aestivum L.). Genetika 49(3): 303-314.

Hucl, P. 1996. Outcrossing rates for 10 Canadian spring wheat cultivars. Canadian Journal of Plant Science 76:423-427

Iskra, J., P. Titan, V. Meglic. 2013. The effect of fluorine atom on the synthesis and composition of gametocidal ethyl oxanilates. Acta Chim. Slov. 60: 561-568

Jantasuriyarat, C., M Vales, C. Watson, O. Riera-Lizarazu. 2004. Identification and mapping of genetic loci affecting the free-threshing habit and spike compactness in wheat (Triticum *aestivum* L.) *Theoretical and Applied Genetics* 108: 261-273.

Jiang, J., W. Raupp, B. Gill. 1992. Rf genes restore fertility in wheat lines with cytoplasms of Elymus trachycaulus and E. ciliaris. Genome 35(4): 614-620.

Johnson, R.R., and C.M. Brown. 1978. Use of DPX 3778 to produce hybrid wheat seed. Crop Science 18: 1026-1028

Johnson, V.A., and J.W. Schmidt. 1968. Hybrid Wheat. Adv. Agron. 36: 145-214.

Karimizadeh, R., M. Mohammadi, N. Sabaghni, A. Mahmoodi, B. Roustami, F. Seyyedi, F. Akbari. 2013. GGE biplot analysis of yield stability in multi-environment trials of lentil genotypes under rainfed condition. Not. Sci. Biol. 5(2): 256-262.

KeHui Z., S. Hong, G. Xiang, W. LinHai, S. YingHui, W. ShaoFang. 2006. Relationship between the genetic distances based on molecular markers and heterosis in hybrid wheat. Journal of Triticeae Crops 26(2): 27-31

Kherde, M.K., I.M. Atkins, O.G. Merkle, K.B. Porter. 1967. Cross pollination studies with male sterile wheats of three cytoplasms, seed size on F1 plants, and seed and anther size of 45 pollinators. Crop Science 7: 389-394.

Kihara, H. 1944. Discovery of the DD-analyser, one of the ancestors of Triticum vulgare. Agric. Hort. 19:889-890.

Lagudah, E.S., and G.M. Halloran. 1987. Phylogenetic relationships of Triticum tauschii the D genome donor to hexaploid wheat. Theoretical and Applied Genetics 75: 592-598.

Lazar, M.D., W.D. Worrall, G.L. Peterson, A.K. Fritz, D. Marshall, L.R. Nelson, L.W. Rooney. 2004. Registration of 'TAM 111' wheat. Crop Science 44(1): 355.

Ling, Hong-Qing., S. Zhao, D. Liu, J. Wang, H. Sun, C. Zhang, H. Fan, D. Li, L. Dong, Y. Tao, C. Gao, H. Wu, Y. Li, Y. Cui, X. Guo, S. Zheng, B. Wang, K. Yu, Q. Liang, W. Yang, X. Lou, J. Chen, M. Feng, J. Jian, X. Zhang. 2013. Draft genome of the wheat A-genome progenitor *Triticum urartu*. Nature 496: 87-90.

Longin, C., J. Muhleisen, H. Maurer, H. Zhang, M. Gowda, J. Reif. 2012. Hybrid breeding in autogamous cereals. Theor. Appl. Genet. 125(6): 1087-1096

Ma, Z.Q., M. Sorrells. 1995. Genetic analysis of fertility restoration in wheat using restriction fragment length polymorphisms. Crop Science 35(4): 1137-1143.

Malla, S., A. Ibrahim, R. Little, S. Kalsbeck, K. Glover, C. Ren. 2010. Comparison of shifted multiplicative model, rank correlation, and biplot analysis for clustering winter wheat production environments. Euphytica 174: 357-370.

Matsuoka, Y. 2011. Evolution of polyploidy *Triticum* wheats under cultivation: the role of domestication, natural hybridization, and allopolyploid speciation in their diversification. Plant Cell Physiology 52(5): 750-764.

Matuschke, I., R. Mishra, M. Qaim. 2007. Adoption and Impact of Hybrid Wheat in India. World Development 35(8): 1422-1435.

Merkle, O.G., K.B. Porter, I.M. Atkins. 1966. Hybrid wheat research in Texas. Texas Agriculture Experiment Station-College Station, Texas.

Mukai, Y., K. Tsunewaki. 1979. Basic studies on hybrid wheat breeding. VIII. A new male sterility-fertility restoration system in common wheat utilizing the cytoplasms of *Aegilops kotschyii* and *Ae. variabilis*. Theoretical Applied Genetics 54: 153-160.

Munaro, L., G. Genin, V. Marchioro, F. Franco, R. Silva, C. Silva, E. Beche. 2014. Brazilian Spring wheat homogeneous adaption regions can be dissected in major megaenvironments. Crop Science 54: 1374-1383.

Murai, K., K. Tsunewaki. 1993. Photoperiod-sensitive cytoplasmic male sterility in wheat with Aegilops crassa cytoplasm. Euphytica 67: 41-48.

Nalam V.J., M. Vales, C. Watson, S. Kianian, O. Riera-Lizarazu. 2006. Map-based analysis of genes affecting the brittle rachis character in tetraploid wheat (Triticum *turgidum* L.). Theoretical and Applied Genetics. 112: 373-381.

Nath, J., J.W. McNay, C.M. Paroda, S.C. Gulati. 1983. Implication of *Triticum searsii* as the B-genome donor to wheat using DNA hybridizations. Biochem Genet 21(7-8): 745-760.

Ohlemeier, Doug. 1999. Kansas Wheat Commission. Jagger variety ranked as Kansas' most planted wheat. Date visited: October 6, 2015. Available at: http://www.seedtoday.com/articles/jagger_variety_ranked_as_kansas___most_planted_wheat-3074.html

Oklahoma Foundation Seed Stocks. 2010. Duster hard red winter wheat. Visited: Oct 6, 2015. Available at: http://www.okgenetics.com/files/Duster%20Brochurefeb%202014.pdf

Peng, J., D. Sun, E. Nevo. 2011. Domestication evolution, genetics and genomics in wheat. Molecular Breeding 28: 281-301.

Pickett, A.A. 1993. Hybrid wheat: results and problems. Advanced Plant Breeding, Suppl. J. Plant Breeding 15: 1-259.

Porter, K.B., G.L. Peterson, J.E. Simmons. 1989. Performance of wheat varieties and hybrids on the high plains of Texas, 1976-1987. Texas AgriLife Experiment Station PR-4652.

Porter, K.B., K.A. Lahr, I.M. Atkins. 1964. Cross-Pollination of male-sterile winter wheat (Triticum aestivum L.) having *Aegilops caudate* L. and *Aegilops ovata* L. cytoplasm. Crop Science 5: 161-163.

Qualset, C.O., K.M. Soliman, C.C. Jan, J. Dvorak, P.E. McGuire, H.E. Vogt. 2005. Registration of UC66049 *Triticum aestivum* blue aleurone genetic stock. Crop Science 45(1): 432.

Ray, D. K., N.D. Mueller, P.C. West, and J.A. Foley. 2013. Yield trends are insufficient to double global crop production by 2050. PLoS ONE 8, e66428.

Reitz, L. P. 1965. The potential of hybrid wheat. Report to the Wheat Quality Conference. P. 36-39. Crop Quality Council, Minneapolis.

Rodriguez-Suarez, C., M.J. Gimenez, N. Gutierrez, C.M. Avila, A. Machado, E. Huttner, M.C. Ramirez, A.C. Martin, A. Castillo, A. Kilian, A. Martin, S.G. Atienza. 2012. Development of wild barley (Hordeum chilense)- derived DArT markers and their use into genetic and physical mapping. Theoretical and Applied Genetics 124(4): 713-722.

Rudd, J.C., R. Devkota, J. Baker, G. Peterson, M. Lazar, B. Bean, D. Worrall, T. Baughman, D. Marshall, R. Sutton, L.W. Rooney, L.R. Nelson, A. Fritz, Y. Weng, G. Morgan, B. Seabourn. 2014. 'TAM 112' wheat, resistant to greenbug And wheat curl mite and adapted to the dryland production system in the Southern High Plains, Journal of Plant Regulation 8:291-297.

Saaten-Union. 2012. The hybrid wheat website. Date visited: September 2, 2015. Available from: http://www.hybridwheat.net/HP/HomePageEN.aspx?idnode=551&.

SAS Institue Inc. 2008. Available at: https://www.sas.com/en_us/home.html. Date visited September 14, 2015.

Shewry, P.R. 2009. Wheat. Journal of Experimental Botany 60.66: 1537-1553.

Simons, K.J., J. Fellers, H. Trick, Z. Zhang, Y-S. Tai, B. Gill, J. Faris. 2006. Molecular characterization of the major wheat domestication gene Q. Genetics 172: 547-555.

Singh, S.K., R. Chatrath, B. Mishra. 2010. Perspective of hybrid wheat research: A review. Indian Journal of Agriculture Sciences 80:1013-1027

Sleper, D., and J. Poehlman. 2006. Breeding Field Crops 5th ed. Blackwell Publishing.

Smith, T. 2012. SAS wins USFA contract for up to five years. Available at: https://www.sas.com/en_gb/news/press-releases/2012/october/us-department-of-agriculture-5.html. Date visited: August 31. 2015

Texas Foundation Seed Service. 2015. Wheat. Date visited: October 6, 2015. Available at: http://tfss.tamu.edu/plant-material/plant-varieties-table/wheat-tam-112/

United States Department of Agriculture- Economic Research Service. 2015. Wheat. Date visited: September 21, 2015. Available at http://www.ers.usda.gov/data-products/wheat-data.aspx.

United States Department of Agriculture- National Agricultural Statistics Service (a). 2015. State Agriculture Overview. Date visited: August 30, 2015. Available at http://www.nass.usda.gov/Statistics_by_State/Texas/.

United States Department of Agriculture- National Agricultural Statistics Service (b). 2015. Crop Production 2014 Summary. Date Visited: October 21, 2015. Available at http://www.usda.gov/nass/PUBS/TODAYRPT/cropan15.pdf

Virmani, S.S., and I.B. Edwards. 1983. Current problems and future prospects for breeding hybrid rice and wheat. Adv. Agron. 36: 145-214.

Whitford R., D. Fleury, J. Reif, M. Garcia, T. Okada, V. Korzun, P. Langridge. 2013 Hybrid breeding in wheat: technologies to improve hybrid wheat seed production. Journal of Experimental Botany, Vol 64.18: 5411-5428. Date visited: August 30, 2015. Available from http://jxb.oxfordjournals.org/content/64/18/5411.full.pdf+html.

Wilson, J.A., and W.M. Ross. 1962. Male sterility interaction of the Triticum Aestivum nucleus and the Triticum timopheevii cytoplasm. Wheat Inform. Serve. 14:29.

Xing, Q.H., Z.G. Ru, C.J. Zhou, X. Xue, C.Y. Liang, D.E. Yang, D.M. Jin, B. Wang. 2003. Genetic analysis, molecular tagging and mapping of the thermos-sensitive genic male-sterile gene (*wtms1*) in wheat. Theoretical Applied Genetics 107: 1500-1504.

Xu, Z., A. Zhang, D. Liu, X. Guo, and S. Zhang. 2002. The heterosis for the kernel weight of main spike and its relation to genetic diversity revealed by RAPD markers in wheat (*Triticum aestivum* L.). Journal of Genetics and Breeding 56(2): 107-111.

Yan, W., L.A. Hunt, Q. Sheng, Z Szlavnics. 2000. Cultivar evaluation and mega-environment investigation based on the GGE biplot. Crop Science 40:597-605

Yan, W. 2001. GGEbiplot-a Windows application for graphical analysis of multi-environment trial data and other types of two way data. Agronomy Journal 93: 1111-1118.

Yan, W., L. A. Hunt. 2002. Biplot Analysis of Multi-Environment Trial Data. In: M. Kang (ed) "Quantitative Genetics, Genomics, and Plant Breeding". CAB International 289-303.

Yan, W., N. Tinker. 2006. Biplot analysis of multi-environment trial data: Principles and applications. Canadian Journal of Plant Science 86: 623-645.

Zhang, A. 1998. Hybrid wheat breeding in the People's Republic of China. In: AE Slinkard (Ed), Preceedings of the Ninth International Wheat Genetics Symposium, University of Saskatchewan University Extension Press, Saskatoon, Canada, 2: 381-383.

Zhang, Y., and M. Kang. 1997. Diallel-SAS: A SAS program for Griffing's Diallel Analysis. Agronomy Journal 89(2): 176-182.

Zhou, K., S. Wang, Y. Feng, Z. Liu, G. Wang. 2006. The 4E-ms system of producing hybrid wheat. Crop Science 46: 250-255.

Zhou, W., F. Kolb, L. Domier, S. Wang. 2004. SSR markers associated with fertility restoration genes against *Triticum timopheevii* cytoplasm in *Triticum aestivum*. Euphytica 141: 33-40.

APPENDIX

Appendix I SAS code used for combined environment ANOVA

```
data uvtB;
input year test_n $ location $ variety $ rep gy yxl;
cards;
;
proc sort; by yxl;
proc glm; by yxl;
class rep(yxl variety;
model gy= rep(yxl) variety;
lsmeans variety;
run;
proc glm;
proc sort; by yxl;
proc univariate normal;
var gy;
run;
proc sort; by yxl;
proc glm;
class variety;
model gy = variety / ss3;
means variety /  hovtest=levene (type=abs);
means variety / hovtest=BARTLETT;
ODS Graphics off;
run;
proc glm;
class yxl rep variety;
model gy= yxl rep(yxl) variety yxl*variety;
test h=yxl e=rep(yxl);
lsmeans yxl variety yxl*variety;
run;
proc glm;
class year location rep variety;
model gy= year location rep(year*location) year*location variety year*variety
location*variety year*location*variety;
test h=year e=rep(year*location);
test h=location e=rep(year*location);
test h=year*location e=rep(year*location);
lsmeans year location year*location variety year*variety location*variety year*location*variety;
means location*variety;
run;
quit;
```

Appendix II List of each variety or advanced breeding line that was used to develop new lines along with the number of times each appears in pedigrees of a line that was part of the Observation Nurseries (SOBS and AOBS) from 2009-2012. Also shows the corresponding percentage of the total number of lines from those years in which it appeared.

Variety or breeding line	Times Used	Percent
TAM 112	505	14.8%
Jagger	295	8.6%
TAM 111	235	6.9%
TAM 303	214	6.3%
TAM 203	179	5.2%
Fannin	170	5.0%
TAM 304	167	4.9%
Pecos	165	4.8%
Mason	148	4.3%
TX02U2508	143	4.2%
TAM 401	139	4.1%
TX01M5009	132	3.9%
Pastor	127	3.7%
Fuller	118	3.5%
Ogallala	117	3.4%
Cutter	100	2.9%
TX92U2317	98	2.9%
TAM 200	96	2.8%
TX01U2598	91	2.7%
JGR	90	2.6%
Bow	89	2.6%
TAM 400	88	2.6%
TX01V6008	87	2.5%
Kauz	82	2.4%
TX99A0153-1	82	2.4%
TX99M5009-28	82	2.4%
HBI0531-A2	80	2.3%
TX88V4505	80	2.3%
TX00D1390	75	2.2%
TAM 113	71	2.1%
TAM 202	69	2.0%
TX00V1131	69	2.0%
TX95D8907	69	2.0%
704 L I-2221	66	1.9%
TX89V4132	66	1.9%
TX97V5300	63	1.8%
Karl 92	62	1.8%

PRL	62	1.8%
TX99A0155	61	1.8%
Trego	60	1.8%
TTCC404	60	1.8%
TX89D1253	60	1.8%
Weebill	59	1.7%
CO960293	58	1.7%
Dumas	58	1.7%
TX02D5813	58	1.7%
TX03M1004	57	1.7%
TX82D5668	57	1.7%
TAM 105	56	1.6%
TX01M5008	55	1.6%
TX01V5719	55	1.6%
BBY	54	1.6%
Century	54	1.6%
NE70654	54	1.6%
TA2450	54	1.6%
ATTILA	53	1.5%
Jagalene	53	1.5%
TX99D4151	50	1.5%
TX02D6112	49	1.4%
WBLL 1	48	1.4%
KS940786-6-9	46	1.3%
TX01A5936	46	1.3%
TX01A7326	45	1.3%
KS84063-9-39-3	44	1.3%
KS950811-5-1	44	1.3%
TX91D6564	44	1.3%
TX92U3060	44	1.3%
X95U104-P66	44	1.3%
Coronado	43	1.3%
Doans	43	1.3%
TX01V5134	43	1.3%
TX90V8410	43	1.3%
TX96D1073	43	1.3%
HD29	42	1.2%
W485	42	1.2%
Ingot	41	1.2%
TX02V7538	41	1.2%
WX93D208-9-1-2	41	1.2%

TX02V7930	40	1.2%
2137	39	1.1%
KS91WGRC11	39	1.1%
TX93V5721	39	1.1%
TX00V1117	38	1.1%
TX03A0123	38	1.1%
TX03V71103	38	1.1%
TX04V072079	38	1.1%
VEE	38	1.1%
1174-27-46	36	1.1%
TX00A0580	36	1.1%
TX01D3215	36	1.1%
X960210	36	1.1%
AEGILOPS SQUARROSA	35	1.0%
BULK SELN	35	1.0%
TX02D5868	35	1.0%
TX98VR8431	35	1.0%
KUKUN	34	1.0%
TX01A7380	33	1.0%
TX02U2557	33	1.0%
WEAVER	33	1.0%
2145	32	0.9%
KAKATSI 'S'	32	0.9%
TX01U2527	32	0.9%
Stanton	31	0.9%
TX03A0382	31	0.9%
TX04V072075	31	0.9%
TX98D2423	31	0.9%
BAU	30	0.9%
DUSTER	30	0.9%
TX02U2510	30	0.9%
KS96HW10-3	29	0.8%
TX97V1613	29	0.8%
2174	28	0.8%
HXL7573	28	0.8%
N566	28	0.8%
OK94P597	28	0.8%
Danby	27	0.8%
TX04A001268	27	0.8%
2180	26	0.8%
TX95V4339	26	0.8%

Bullet	25	0.7%
Intrada	25	0.7%
TX99A0136	25	0.7%
KSS9011-1-33 IP64	24	0.7%
TAM 107	24	0.7%
TAM 109	24	0.7%
TX03V73097	24	0.7%
CTK78	23	0.7%
OVERLEY	23	0.7%
TX03A0378	23	0.7%
TX03A0451	23	0.7%
TX78V3620	23	0.7%
TX87V1233	23	0.7%
CL0619	22	0.6%
TAM 110	22	0.6%
TX02A0341	22	0.6%
W03-20	22	0.6%
FREEDOM	21	0.6%
HV9W99-558	21	0.6%
IKE	21	0.6%
RonL	21	0.6%
TOMAHAWK	21	0.6%
TX01V5838	21	0.6%
TX03A0309	21	0.6%
TX04M410212	21	0.6%
TX93V5723	21	0.6%
TX96U8618	21	0.6%
TX97V2836	21	0.6%
TX99U8618	21	0.6%
TXGH10440	21	0.6%
U1254-7-9-2-1	21	0.6%
BABAX	20	0.6%
FLORIDA 304	20	0.6%
OVL	20	0.6%
Thunderbolt	20	0.6%
TNMU	20	0.6%
Croc 1	19	0.6%
Kipacoma	19	0.6%
MILAN	19	0.6%
TX01U2699	19	0.6%
TX01V5136	19	0.6%

TX04V076015	19	0.6%
BAV92	18	0.5%
TX01A7340	18	0.5%
TX02V7937	18	0.5%
TX03M1214	18	0.5%
W95-301	18	0.5%
OK03522	17	0.5%
Ok98699	17	0.5%
PIFED	17	0.5%
PJN	17	0.5%
SERI1B	17	0.5%
TUKURU	17	0.5%
BJY	16	0.5%
BUC	16	0.5%
KS990498-3-&~2	16	0.5%
TX01V6219	16	0.5%
TX03A0272	16	0.5%
TX03V74043	16	0.5%
TX04M410082	16	0.5%
TX05A001844	16	0.5%
X940748-2-4	16	0.5%
X940786-6-7	16	0.5%
205	15	0.4%
2163	15	0.4%
97T1154	15	0.4%
AP04T W9819	15	0.4%
COC	15	0.4%
ENDURANCE	15	0.4%
KS03HW155-2	15	0.4%
KS03HW156-3	15	0.4%
OK03318	15	0.4%
OK92403	15	0.4%
OK94P549-11	15	0.4%
OK95553	15	0.4%
P961341	15	0.4%
TUI	15	0.4%
TX01A5937	15	0.4%
TX03M1037	15	0.4%
TX03M1179	15	0.4%
TX86A8072	15	0.4%
TX94D7091	15	0.4%

TX96V2627	15	0.4%
Yumar	15	0.4%
KS01HW152-6	14	0.4%
OK99610	14	0.4%
PEWIT1	14	0.4%
TX02D6241	14	0.4%
TX02V7421	14	0.4%
TX04A001008	14	0.4%
TX87A6763	14	0.4%
TX88A6848	14	0.4%
TX93D2385	14	0.4%
TX93V4315	14	0.4%
VORONA	14	0.4%
97T1018	13	0.4%
ABI 86*3414	13	0.4%
AMAD	13	0.4%
ARLIN	13	0.4%
Barbet	13	0.4%
CHIL	13	0.4%
HP 1731	13	0.4%
KS00F5--20-3-2	13	0.4%
KS03HW157-1	13	0.4%
Laken	13	0.4%
OK94406	13	0.4%
OLA	13	0.4%
PARUS	13	0.4%
TX04M410139	13	0.4%
TX96V2427	13	0.4%
TX98V6239	13	0.4%
X84W063-9-39-2	13	0.4%
AMI	12	0.4%
Cisco	12	0.4%
DELIVER	12	0.4%
F59	12	0.4%
HEVO	12	0.4%
HN7	12	0.4%
KS04WKS-19	12	0.4%
KS06O3A~33	12	0.4%
KS950423-I-1	12	0.4%
NAI80	12	0.4%
SDY	12	0.4%

TX00D1256	12	0.4%
TX01V5722	12	0.4%
TX01V6334	12	0.4%
TX04A001246	12	0.4%
TX71A1039V1	12	0.4%
TX94VT938-6	12	0.4%
TX98V8166	12	0.4%
ALTAR 84	11	0.3%
Everest	11	0.3%
FL931339AS	11	0.3%
HVA114	11	0.3%
KSS9011-1-14 IP45	11	0.3%
OCW00M618S-1B	11	0.3%
OK78047	11	0.3%
PSN 'S'	11	0.3%
STAR	11	0.3%
Star derived	11	0.3%
T200	11	0.3%
TX01V5639	11	0.3%
TX03A0260	11	0.3%
TX04M410067	11	0.3%
TX96D2240	11	0.3%
TX97A0169	11	0.3%
TX98A0190	11	0.3%
VERDE	11	0.3%
W1062A	11	0.3%
W3416	11	0.3%
W97-234	11	0.3%
WI89-189-14	11	0.3%
X05A515	11	0.3%
211	10	0.3%
2157 'S'	10	0.3%
Agri-Pro 4342	10	0.3%
ARH	10	0.3%
Betty	10	0.3%
CSM	10	0.3%
FRTL	10	0.3%
GAA	10	0.3%
HBF0290	10	0.3%
HBK0075	10	0.3%
KB8	10	0.3%

KM 1022-2-90	10	0.3%
KSS9011-1-21 IP52	10	0.3%
KSS9011-1-27 IP58	10	0.3%
Lockett	10	0.3%
OCW00S106S-1B	10	0.3%
OK01519	10	0.3%
OK95G703-98-61416	10	0.3%
PFAU	10	0.3%
SCAB-7	10	0.3%
TX00V1429	10	0.3%
TX03A0044	10	0.3%
TX03A0121	10	0.3%
TX04A001797	10	0.3%
TX04A001830	10	0.3%
TX04V071069	10	0.3%
TX96V2889	10	0.3%
TX98U8184	10	0.3%
TX99A0248-2	10	0.3%
W2440	10	0.3%
W8427	10	0.3%
X01A359	10	0.3%
X05A546	10	0.3%
BATAVIA	9	0.3%
BORL95	9	0.3%
C801	9	0.3%
CO995080	9	0.3%
FARMEC	9	0.3%
JAG	9	0.3%
KS94U275	9	0.3%
KS950352-M-4	9	0.3%
KS970274	9	0.3%
N44	9	0.3%
OCW00M727S-1B	9	0.3%
OK02232	9	0.3%
OK03716W	9	0.3%
OK91724	9	0.3%
PI137739	9	0.3%
TX02A0577	9	0.3%
TX03A0563	9	0.3%
TX87V1613	9	0.3%
TX94V2140	9	0.3%

TX97A0122	9	0.3%
TX98D2316	9	0.3%
TX98D3456	9	0.3%
TX99A6634	9	0.3%
W99-194	9	0.3%
WHEATEAR	9	0.3%
X01A383	9	0.3%
X05A567	9	0.3%
Custer	8	0.2%
HBK1064-6	8	0.2%
HUI	8	0.2%
KBLR 22	8	0.2%
KS01HW55	8	0.2%
KS93U134	8	0.2%
KS970274-14	8	0.2%
ND 800	8	0.2%
OK01307	8	0.2%
PI????	8	0.2%
SAPI	8	0.2%
TEAL	8	0.2%
TX01U2601	8	0.2%
TX02D5275	8	0.2%
TX02V7411	8	0.2%
TX03A0182	8	0.2%
TX03M1017	8	0.2%
TX04M410127	8	0.2%
TX99V3034	8	0.2%
URES	8	0.2%
W99-331	8	0.2%
X05A463	8	0.2%
X05A601	8	0.2%
CHAPIO 'S'	7	0.2%
CNDO	7	0.2%
ENTE	7	0.2%
JUN	7	0.2%
KSS9011-1-5 IP36	7	0.2%
LOHARI Y91-92 NO70	7	0.2%
LONG92-1638	7	0.2%
Mexi 2	7	0.2%
MINO	7	0.2%
MvC324-96	7	0.2%

ND 741	7	0.2%
NEMURA	7	0.2%
NW01L2019	7	0.2%
OK102	7	0.2%
R143	7	0.2%
RWA177-B2-2	7	0.2%
Sequia 7	7	0.2%
SERI	7	0.2%
T monococcum	7	0.2%
TRAP	7	0.2%
TX02D6222	7	0.2%
TX02V7525	7	0.2%
TX02V7615	7	0.2%
TX03M1066	7	0.2%
TX03V76009	7	0.2%
TX03V76057	7	0.2%
TX04A001771	7	0.2%
TX81V6582	7	0.2%
TX84V1307	7	0.2%
TX98A5424	7	0.2%
TX98D1073	7	0.2%
TX98D1158	7	0.2%
TX99A6611	7	0.2%
TX99V3033	7	0.2%
U1254-1-5-2-1	7	0.2%
U1254-4-4-9-1	7	0.2%
W04-417	7	0.2%
Walworth	7	0.2%
WL711	7	0.2%
X01A187	7	0.2%
X01A376	7	0.2%
X05A494	7	0.2%
X05A577	7	0.2%
X05A608	7	0.2%
X05A663	7	0.2%
X05A682	7	0.2%
X05A691	7	0.2%
1BL1RS	6	0.2%
93HW242	6	0.2%
98HW165	6	0.2%
98HW423	6	0.2%

ABI	6	0.2%
ALDAN	6	0.2%
ARL	6	0.2%
BULK SELN 00F5- 52-4	6	0.2%
BULK SELN 00F5-11-2	6	0.2%
CHAKINSKAYA 306	6	0.2%
CORYDON	6	0.2%
G990624	6	0.2%
GRANGER	6	0.2%
KB9	6	0.2%
KOEL	6	0.2%
KS01HW163-4	6	0.2%
KS04HW79	6	0.2%
KS91W009-6-1	6	0.2%
KS940786-6-7	6	0.2%
KS96WGRC39	6	0.2%
KSS9011-1-41 IP72	6	0.2%
KSS9011-1-43 IP74	6	0.2%
NNSGP90-13	6	0.2%
O3A-B7	6	0.2%
OK04119	6	0.2%
OK05303	6	0.2%
OK94P461	6	0.2%
OK95548	6	0.2%
OK96717-6756	6	0.2%
OPATA	6	0.2%
ORO BLANCO	6	0.2%
PVN	6	0.2%
RAYON	6	0.2%
RWA177-B2-4	6	0.2%
RWA177-B2-6	6	0.2%
RWA-Dn7	6	0.2%
SELYANKA	6	0.2%
SKAUZ	6	0.2%
TAUS	6	0.2%
TNK	6	0.2%
TX01V5425	6	0.2%
TX02A0785CL	6	0.2%
TX02U2608	6	0.2%
TX02V7406	6	0.2%
TX03V75096	6	0.2%

TX04A001688	6	0.2%
TX04M410132	6	0.2%
TX04M410145	6	0.2%
TX71A106-5	6	0.2%
TX86A5606	6	0.2%
TXHBG0358	6	0.2%
U4551B-R11-2R-1	6	0.2%
WGRC15	6	0.2%
WX97046	6	0.2%
X05A452	6	0.2%
X05A474	6	0.2%
X05A582	6	0.2%
X05A584	6	0.2%
X05A604	6	0.2%
X05A647	6	0.2%
X05A657	6	0.2%
X05A662	6	0.2%
X05A667	6	0.2%
YUMA	6	0.2%
286P1-111	5	0.1%
5270	5	0.1%
AP04T 8109	5	0.1%
AP04T9229	5	0.1%
ARYNEL 2222	5	0.1%
CLC89	5	0.1%
CNO79	5	0.1%
G001784	5	0.1%
G980039	5	0.1%
GA911316-E-4-5	5	0.1%
GUYMON	5	0.1%
HAHN	5	0.1%
HBZ588B	5	0.1%
HE1	5	0.1%
HV9W03-696R	5	0.1%
Jackpot	5	0.1%
KaJagger	5	0.1%
KEA	5	0.1%
KS015538	5	0.1%
KS06O3A~49	5	0.1%
KS91H184	5	0.1%
KS92WGRC16	5	0.1%

KS93U69	5	0.1%
KS940935-125-5-2	5	0.1%
KS980512	5	0.1%
KS990494-11-~O	5	0.1%
KSS9011-1-10 IP41	5	0.1%
KSS9011-1-18 IP49	5	0.1%
KSWGRC39	5	0.1%
LAJ3302	5	0.1%
LRO	5	0.1%
MANNIKIN 2	5	0.1%
MvC426-96	5	0.1%
NE99554	5	0.1%
O3A-B8	5	0.1%
OASIS	5	0.1%
OCW00S185S-1B	5	0.1%
OK05723W	5	0.1%
OK94P455	5	0.1%
Platte	5	0.1%
SD97380-2	5	0.1%
SWM866442	5	0.1%
TAM 302	5	0.1%
THB	5	0.1%
TSAPKI	5	0.1%
TX00A562-2	5	0.1%
TX01V5915	5	0.1%
TX02D6253	5	0.1%
TX02V7426	5	0.1%
TX02V7438	5	0.1%
TX03A0216	5	0.1%
TX03M1016	5	0.1%
TX04M410228	5	0.1%
TX05A001868	5	0.1%
TX84U4094-16	5	0.1%
TX94D4360	5	0.1%
TX94V2136	5	0.1%
TX97A0149	5	0.1%
TX99U8544	5	0.1%
W98-442	5	0.1%
WL6718	5	0.1%
X01A369	5	0.1%
X05A459	5	0.1%

X05A460	5	0.1%
X05A498	5	0.1%
X05A503	5	0.1%
X05A542	5	0.1%
X05A547	5	0.1%
X05A553	5	0.1%
X05A556	5	0.1%
X05A560	5	0.1%
X05A565	5	0.1%
X05A566	5	0.1%
X05A569	5	0.1%
X05A578	5	0.1%
X05A581	5	0.1%
X05A642	5	0.1%
X05A671	5	0.1%
X05A692	5	0.1%
X05A699	5	0.1%
YACO	5	0.1%
02SR811	4	0.1%
2172	4	0.1%
224	4	0.1%
ANA	4	0.1%
AP04T9029	4	0.1%
AP04TW1318	4	0.1%
APO2T 4605	4	0.1%
AUS1408	4	0.1%
BL 1496	4	0.1%
CAR422	4	0.1%
CASKOR	4	0.1%
CAZO	4	0.1%
China 158	4	0.1%
CO970943	4	0.1%
Glenlivet	4	0.1%
HBZ356A	4	0.1%
HBZ621A	4	0.1%
HEYNE 'S'	4	0.1%
HUW234+LR34	4	0.1%
IRENA	4	0.1%
KAMBI	4	0.1%
KS010525-1-1	4	0.1%
KS020482TM~2	4	0.1%

KS86231B-10-1	4	0.1%
KS980421-1-4-#2	4	0.1%
KS980512-11-24	4	0.1%
KS980512-11-9	4	0.1%
KS980554-12-~9	4	0.1%
KS98W0512-2-~4	4	0.1%
KSS9011-1-45 IP76	4	0.1%
KSS9011-1-50 IP81	4	0.1%
MJI	4	0.1%
MO88	4	0.1%
NORM	4	0.1%
NuHills	4	0.1%
O3A-B6	4	0.1%
OIT 3729	4	0.1%
OK02321	4	0.1%
OK94P544	4	0.1%
PBW65	4	0.1%
PIOS	4	0.1%
RWA181-B1-1	4	0.1%
RWA181-B1-6	4	0.1%
RWA181-B1-7	4	0.1%
SD99W028	4	0.1%
TOB	4	0.1%
TRM	4	0.1%
TX00A0536	4	0.1%
TX00D2234	4	0.1%
TX01U2503	4	0.1%
TX02A0650	4	0.1%
TX02U2602	4	0.1%
TX03M1151	4	0.1%
TX04A001819	4	0.1%
TX04M410283	4	0.1%
TX04V073035	4	0.1%
TX05A001846	4	0.1%
TX88A6880	4	0.1%
TX93D2066	4	0.1%
TX99A0556	4	0.1%
TX99D4572	4	0.1%
TX99V2437	4	0.1%
Ventor	4	0.1%
X05A453	4	0.1%

X05A475	4	0.1%
X05A526	4	0.1%
X05A583	4	0.1%
X05A611	4	0.1%
X05A679	4	0.1%
X05A690	4	0.1%
X920866-B-7	4	0.1%
128	3	0.1%
2158	3	0.1%
Above	3	0.1%
Acc# 991149	3	0.1%
ALPOWA	3	0.1%
AMSEL 'S'	3	0.1%
AP02T4343	3	0.1%
AP04TW9819	3	0.1%
Aspen	3	0.1%
BIG DAWG	3	0.1%
Briggs	3	0.1%
BULK SELN 00F5-31-1	3	0.1%
CIMMYT E95Syn4152-30	3	0.1%
CIMMYT E95Syn4152-37	3	0.1%
CNO67	3	0.1%
CRR	3	0.1%
CTY	3	0.1%
CUPE	3	0.1%
Destin	3	0.1%
DOSVID	3	0.1%
ERA	3	0.1%
FFR525W	3	0.1%
G980122	3	0.1%
Gk Forrass	3	0.1%
HBG 0358	3	0.1%
HBK0935-13-6	3	0.1%
HKK	3	0.1%
HTG	3	0.1%
HV9W96-1270R-1	3	0.1%
Kakhu	3	0.1%
KANCHAN	3	0.1%
KS010474-11-2	3	0.1%
KS01HW54	3	0.1%
KS06O3A~24	3	0.1%

KS06O3A~42	3	0.1%
KS91H174	3	0.1%
KS92WGRC26	3	0.1%
KS980478-3-~5	3	0.1%
KS980512-11-~3	3	0.1%
KS980512-11-22	3	0.1%
KS990159-3-~11	3	0.1%
MIT	3	0.1%
MTRWA92155	3	0.1%
ND 801	3	0.1%
NuDAKOTA	3	0.1%
O3A-B3	3	0.1%
OAS	3	0.1%
OCW00M777T-1B	3	0.1%
OCW00S047S-3B	3	0.1%
OK00611W	3	0.1%
OK02516	3	0.1%
OK03230	3	0.1%
OK04525	3	0.1%
OK93P634	3	0.1%
OK94A549-98-662	3	0.1%
PLO	3	0.1%
Prowers	3	0.1%
PYN	3	0.1%
RWA177-B2-5	3	0.1%
Sequia 6	3	0.1%
SHA7	3	0.1%
SHARK	3	0.1%
SWM7094	3	0.1%
TA2460	3	0.1%
TTCC682	3	0.1%
TX01D1390	3	0.1%
TX01D3472	3	0.1%
TX02D6273	3	0.1%
TX02D6913	3	0.1%
TX03A0148	3	0.1%
TX04A001785	3	0.1%
TX04A001795	3	0.1%
TX04M410073	3	0.1%
TX04M410186	3	0.1%
TX04V075019	3	0.1%

TX04V076012	3	0.1%
TX90A9528	3	0.1%
TX95V5314	3	0.1%
TX95V6214	3	0.1%
TX98D4151	3	0.1%
TX99A0154	3	0.1%
TXV2818-A1	3	0.1%
VASCO	3	0.1%
VBF0154-4'S'	3	0.1%
VBF0589-1	3	0.1%
W96x1311-01	3	0.1%
WH576	3	0.1%
X05A458	3	0.1%
X05A486	3	0.1%
X05A511	3	0.1%
X05A520	3	0.1%
X05A534	3	0.1%
X05A537	3	0.1%
X05A539	3	0.1%
X05A555	3	0.1%
X05A573	3	0.1%
X05A575	3	0.1%
X05A602	3	0.1%
X05A605	3	0.1%
X05A606	3	0.1%
X05A658	3	0.1%
X05A672	3	0.1%
01SR815	2	0.1%
02SR784	2	0.1%
02SR789	2	0.1%
135U6-1	2	0.1%
97ROBINOF	2	0.1%
AGSECO 7853	2	0.1%
AMADINA	2	0.1%
AP04T9225	2	0.1%
Armour	2	0.1%
ASP	2	0.1%
BAW898	2	0.1%
BB	2	0.1%
BCN	2	0.1%
BLT	2	0.1%

BUL 105612186	2	0.1%
BULK SELN 00F5-14-7	2	0.1%
CIMMYT E2Syn4153-24	2	0.1%
CIMMYT E2Syn4153-8	2	0.1%
CO980376	2	0.1%
CO99314	2	0.1%
DOVE	2	0.1%
F4105W21	2	0.1%
G03601-7	2	0.1%
G982163	2	0.1%
Halbred	2	0.1%
HBB313E	2	0.1%
HBK0771-22-1W	2	0.1%
I CHURRINCHE	2	0.1%
IAS58	2	0.1%
IL89-6483	2	0.1%
ITD	2	0.1%
KAL	2	0.1%
KASORO 3	2	0.1%
KrasSkaya 25	2	0.1%
KS015560	2	0.1%
KS06O3A~50	2	0.1%
KS90WGRC10	2	0.1%
KS91015-C-6	2	0.1%
KS970187-1-10	2	0.1%
KS980191-1-2-#2	2	0.1%
KS990159-3-7	2	0.1%
KS990160-4-~3	2	0.1%
KSS9011-1-4 IP35	2	0.1%
LR42	2	0.1%
MIR 61	2	0.1%
MV04-96	2	0.1%
ND	2	0.1%
NE00679	2	0.1%
NW01L2023	2	0.1%
NW97112	2	0.1%
O3A-89-2	2	0.1%
OK00614	2	0.1%
OK01325	2	0.1%
OK01701	2	0.1%
OK02508	2	0.1%

OK02619	2	0.1%
OK90604	2	0.1%
OK94P549-99-670	2	0.1%
OK95616-6756	2	0.1%
OK98697	2	0.1%
OK99215	2	0.1%
OK9962546	2	0.1%
PEWIT 3	2	0.1%
POSTROCK	2	0.1%
PRINIA	2	0.1%
RB	2	0.1%
RL4137	2	0.1%
SHOCKER	2	0.1%
SRMA	2	0.1%
T-119	2	0.1%
T129	2	0.1%
THK	2	0.1%
TTCC578	2	0.1%
TTCC58	2	0.1%
TX00D1622	2	0.1%
TX01V5031	2	0.1%
TX01V5413	2	0.1%
TX02A0078	2	0.1%
TX02D5996	2	0.1%
TX02D6249	2	0.1%
TX02V7418	2	0.1%
TX04M410008	2	0.1%
TX90A9516	2	0.1%
TX90V7911	2	0.1%
TX93A9024	2	0.1%
TX95A1161	2	0.1%
TX98-87	2	0.1%
TX98A0010	2	0.1%
TX98U8618	2	0.1%
TX98V9437	2	0.1%
TX98VR8426	2	0.1%
TX994151	2	0.1%
TX99A0638	2	0.1%
TX99D3462	2	0.1%
TX99V4572	2	0.1%
TXGH13622	2	0.1%

VG9144	2	0.1%
W 97-234	2	0.1%
W189-163W	2	0.1%
Wintex	2	0.1%
X00A27	2	0.1%
X01A358	2	0.1%
X01A375	2	0.1%
X01A377	2	0.1%
X01A7380	2	0.1%
X05A457	2	0.1%
X05A461	2	0.1%
X05A471	2	0.1%
X05A476	2	0.1%
X05A502	2	0.1%
X05A524	2	0.1%
X05A536	2	0.1%
X05A540	2	0.1%
X05A541	2	0.1%
X05A544	2	0.1%
X05A554	2	0.1%
X05A574	2	0.1%
X05A609	2	0.1%
X05A610	2	0.1%
X05A641	2	0.1%
X05A646	2	0.1%
X05A649	2	0.1%
X05A670	2	0.1%
X91V133	2	0.1%
XIANG822661	2	0.1%
1078-2KK	1	0.0%
1390	1	0.0%
53-97 Turda	1	0.0%
5RL-1	1	0.0%
8156	1	0.0%
Amigo	1	0.0%
AP04T 9220	1	0.0%
Arapahoe	1	0.0%
B1551-WH	1	0.0%
BAGE	1	0.0%
BEZ	1	0.0%
BUCK85180	1	0.0%

BULK SELN 00F5-32-11	1	0.0%
BULK SELN 00F5-42-5	1	0.0%
BULK SELN 00F5-50-1	1	0.0%
BZA	1	0.0%
CHEN	1	0.0%
CI 9321	1	0.0%
CIMMYT E95Syn4152-32	1	0.0%
CIMMYT E95Syn4152-8	1	0.0%
CIMMYT-53	1	0.0%
CMH72A508	1	0.0%
CMH73A329	1	0.0%
CO980704	1	0.0%
COKER 9663	1	0.0%
COKER983	1	0.0%
COLLIN	1	0.0%
CS5A	1	0.0%
CST	1	0.0%
DH432893	1	0.0%
DM 6167	1	0.0%
EFED	1	0.0%
ER6789-86	1	0.0%
Erythrospermum	1	0.0%
F95948G1-4	1	0.0%
FN	1	0.0%
FRET 2	1	0.0%
G980029	1	0.0%
G980172	1	0.0%
G982238-2	1	0.0%
G990672	1	0.0%
GA 80078-1980	1	0.0%
HBC197F-1	1	0.0%
HCF012	1	0.0%
HGF112	1	0.0%
HUW234	1	0.0%
HYS	1	0.0%
IAS64	1	0.0%
ICAB	1	0.0%
KB15	1	0.0%
KB5	1	0.0%
KB7	1	0.0%
KRAPETC	1	0.0%

KS00A758	1	0.0%
KS00HW175-4	1	0.0%
KS00HW183	1	0.0%
KS00U758	1	0.0%
KS010514-9-3	1	0.0%
KS82W418	1	0.0%
KS94U326	1	0.0%
KS950412-F-2	1	0.0%
KS97W0935-29-15	1	0.0%
KS98HW122	1	0.0%
KSS9011-1-37 IP68	1	0.0%
KT	1	0.0%
Largo	1	0.0%
LR34	1	0.0%
MILVUS 3	1	0.0%
MOREY	1	0.0%
MRL	1	0.0%
MVC327-96	1	0.0%
MVC422-96	1	0.0%
ND 751	1	0.0%
NE00556	1	0.0%
NUPA	1	0.0%
NW975112	1	0.0%
OK00411	1	0.0%
OK01225	1	0.0%
OK02126	1	0.0%
OK02522	1	0.0%
OK02901C	1	0.0%
OK86216	1	0.0%
OK91783	1	0.0%
OK93P656-3299	1	0.0%
OK95548-6654	1	0.0%
OK98135	1	0.0%
OK98690	1	0.0%
OK99201	1	0.0%
OK99212	1	0.0%
OK99216	1	0.0%
PEG	1	0.0%
PI 593688	1	0.0%
PI 595757	1	0.0%
PICUS	1	0.0%

RWA177-B2-10	1	0.0%
SAULESKU 17	1	0.0%
SD97089-1	1	0.0%
SNI	1	0.0%
Stephens	1	0.0%
Sturdy 2K	1	0.0%
TA759	1	0.0%
TAM W-101	1	0.0%
TEMU12375	1	0.0%
TURKEY13 RESEL	1	0.0%
TX00V5425	1	0.0%
TX01A7427	1	0.0%
TX01U2508	1	0.0%
TX01V5135	1	0.0%
TX01V6037	1	0.0%
TX02D5995	1	0.0%
TX02D6239	1	0.0%
TX02D7023	1	0.0%
TX03A0297	1	0.0%
TX03A0364	1	0.0%
TX04A001058	1	0.0%
TX04A001730	1	0.0%
TX04M410037	1	0.0%
TX04M410246	1	0.0%
TX04V076084	1	0.0%
TX86V1540	1	0.0%
TX88V4721	1	0.0%
TX89V4133	1	0.0%
TX93D1064	1	0.0%
TX95V5905	1	0.0%
TX96V7234	1	0.0%
TX98D1027	1	0.0%
TX98D4032	1	0.0%
TX99A0383-2	1	0.0%
TX99A0562-2	1	0.0%
TX99A0635	1	0.0%
TX99A6030	1	0.0%
TX99V3027-A1	1	0.0%
TXGH12588-105	1	0.0%
TXHBE0726	1	0.0%
W0405D	1	0.0%

W462	1	0.0%
W7469C	1	0.0%
white	1	0.0%
WX99D106-P49	1	0.0%
X01A357	1	0.0%
X01A363	1	0.0%
X01A385	1	0.0%
X01A386	1	0.0%
X05A454	1	0.0%
X05A485	1	0.0%
X05A495	1	0.0%
X05A497	1	0.0%
X05A500	1	0.0%
X05A506	1	0.0%
X05A527	1	0.0%
X05A529	1	0.0%
X05A538	1	0.0%
X05A550	1	0.0%
X05A557	1	0.0%
X05A561	1	0.0%
X05A563	1	0.0%
X05A571	1	0.0%
X05A576	1	0.0%
X05A579	1	0.0%
X05A645	1	0.0%
X05A650	1	0.0%
X05A660	1	0.0%
X05A695	1	0.0%
X920663-A-10-1	1	0.0%
X921084-C-8-2	1	0.0%
X950677-2	1	0.0%
YMH	1	0.0%

Appendix III List of each variety or advanced breeding line that was used to develop new lines along with the number of times each appears in pedigrees of a line that was part of the Advanced Yield Trials (STA and AA) from 2011-2014. Also shows the corresponding percentage of the total number of lines from those years in which it appeared. The mean yield of the progeny of each variety or breeding line is also shown.

Variety or breeding line	Times Used	Percent	Mean Yield (kg/ha)
TAM 112	92	18.4%	2939.77
TAM 111	63	12.6%	2981.67
TAM 303	46	9.2%	2912.04
Jagger	43	8.6%	3086.91
Pecos	25	5.0%	3274.82
TAM 304	25	5.0%	3020.58
TAM 401	23	4.6%	3135.05
Ogallala	21	4.2%	3262.08
Mason	20	4.0%	3044.53
TX02U2508	20	4.0%	3211.57
TAM 203	19	3.8%	3261.23
TX92U2317	19	3.8%	3518.03
TX99A0153-1	19	3.8%	3474.57
Fannin	18	3.6%	3277.35
TX01V6008	18	3.6%	3198.07
TAM 113	17	3.4%	3301.52
TX95D8907	17	3.4%	3498.57
TX96D1073	16	3.2%	2801.28
Trego	15	3.0%	3174.37
TAM 202	14	2.8%	3271.31
TX99A0155	14	2.8%	2998.22
TX00D1390	13	2.6%	3473.60
Cutter	12	2.4%	2946.18
Kauz	12	2.4%	3314.87
TAM 200	11	2.2%	3385.24
TX00V1131	11	2.2%	2802.53
TX03V71103	11	2.2%	3511.81
TX99U8618	11	2.2%	2435.16
Pastor	10	2.0%	3400.37
CO960293	10	2.0%	3387.39
KS005F5	10	2.0%	3345.83
TX02D6112	10	2.0%	3236.75
Weebill	10	2.0%	3338.08
KS84063-9-39-3	9	1.8%	3528.50
TX01V5719	9	1.8%	2904.57

TX04V072079	9	1.8%	3421.55
TX90V8410	9	1.8%	3528.50
TX97V5300	9	1.8%	2710.33
RonL	8	1.6%	3418.25
TTCC404	8	1.6%	3632.68
TX02D5813	8	1.6%	3128.17
TX03M1004	8	1.6%	3315.78
TX04V072075	8	1.6%	3590.47
TX89D1253	8	1.6%	3632.68
Stanton	7	1.4%	3004.94
TAM 400	7	1.4%	3118.56
2145	7	1.4%	3128.15
CTK78	7	1.4%	3140.12
Doans	7	1.4%	3166.70
Dumas	7	1.4%	2846.15
HALBERD	7	1.4%	2133.89
HBI0531-A2	7	1.4%	3440.35
TX01M5009-28	7	1.4%	2809.95
TX01U2598	7	1.4%	2871.97
TX03A0309	7	1.4%	3478.69
TX87V1233	7	1.4%	3140.12
TX88V4505	7	1.4%	3440.35
TX99M5009-28	7	1.4%	3362.72
KS940786	6	1.2%	3033.90
TAM 105	6	1.2%	2927.21
THUNDERBOLT	6	1.2%	2314.40
704 L I-2221	6	1.2%	2989.25
KARL 92	6	1.2%	3706.93
TX01A7380	6	1.2%	3305.70
TX05A001844	6	1.2%	3503.03
TX78V3620	6	1.2%	3171.22
TX89V4132	6	1.2%	2989.25
TX95V4339	6	1.2%	3346.41
TX97V2836	6	1.2%	2627.62
TX99D4151	6	1.2%	2651.71
X940748-2-4	6	1.2%	3503.03
X940786-6-7	6	1.2%	3503.03
NE70654	5	1.0%	3128.10
OK03318	5	1.0%	3523.65
OK92403	5	1.0%	3523.65
OK95553	5	1.0%	3523.65

TA2450	5	1.0%	3128.10
1174-27-46	5	1.0%	2869.71
ATTILA	5	1.0%	3218.52
BBY	5	1.0%	3128.10
BOW"S"	5	1.0%	3128.10
Century	5	1.0%	3128.10
Coronado	5	1.0%	2869.71
TX01M5009	5	1.0%	2694.13
TX01V5134	5	1.0%	3366.94
TX02V7930	5	1.0%	3586.44
TX03A0272	5	1.0%	2583.93
TX03A0378	5	1.0%	3108.36
TX03A0451	5	1.0%	3392.27
TX03M1037	5	1.0%	2736.35
TX82D5668	5	1.0%	3322.35
TX98D2423	5	1.0%	2516.01
TX98V6239	5	1.0%	2730.18
U1254	5	1.0%	2977.75
WEAVER	5	1.0%	3354.72
WX93D208-9-1-2	5	1.0%	3771.45
X01A359	5	1.0%	3022.93
X960210	5	1.0%	2869.71
KUKUN	4	0.8%	3669.99
PRL	4	0.8%	3302.33
RWA177-B2	4	0.8%	2523.03
SERI.1B	4	0.8%	2966.49
TAM 107	4	0.8%	3232.55
TUKURU	4	0.8%	3427.90
2137	4	0.8%	3710.18
2174	4	0.8%	3037.77
AMAD	4	0.8%	2966.49
FULLER	4	0.8%	3497.25
HEVO	4	0.8%	2966.49
Ingot	4	0.8%	3069.93
Kipacoma	4	0.8%	2996.83
TX00V1117	4	0.8%	3538.48
TX01D3215	4	0.8%	2991.62
TX01U2527	4	0.8%	2741.71
TX02D5868	4	0.8%	3093.13
TX02U2510	4	0.8%	3409.33
TX02V7538	4	0.8%	3144.41

TX03A0123	4	0.8%	3356.09
TX04A001246	4	0.8%	3797.21
TX91D6564	4	0.8%	3079.04
TX92U3060	4	0.8%	3079.04
TX94VT938-6	4	0.8%	3797.21
TX96U8618	4	0.8%	2740.16
TX98A0190	4	0.8%	3173.53
TX98VR8431	4	0.8%	2565.72
X05A567	4	0.8%	2996.83
X95U104-P66	4	0.8%	3079.04
KS03HW155-2	3	0.6%	3096.29
KS03HW156-3	3	0.6%	2770.02
KS91WGRC11	3	0.6%	2894.34
OK94P549	3	0.6%	3264.42
OK99610	3	0.6%	3244.85
RWA181-B1	3	0.6%	2665.43
SA93 OK04819	3	0.6%	3640.15
SHARK-3	3	0.6%	3640.15
T107	3	0.6%	2785.81
T200	3	0.6%	2701.36
Bullet	3	0.6%	3052.81
Danby	3	0.6%	3675.50
Intrada W	3	0.6%	2900.32
Jagelene	3	0.6%	3230.54
KS015538	3	0.6%	2635.40
KS01HW55	3	0.6%	3079.48
TX00V1429	3	0.6%	3005.73
TX01A5936	3	0.6%	3087.13
TX01A7326	3	0.6%	3381.67
TX01V6334	3	0.6%	2379.58
TX02U2557	3	0.6%	3399.49
TX04A001268	3	0.6%	3290.90
TX04A001819	3	0.6%	3573.03
TX5009	3	0.6%	2067.32
TX86V1540	3	0.6%	2701.36
TX93V5721	3	0.6%	3381.67
Yumar	3	0.6%	2601.92
KS93U134	2	0.4%	3640.34
KS94U275	2	0.4%	3518.28
KS950423-I-1	2	0.4%	2869.19
KSS9011-1-33 IP64	2	0.4%	3377.27

KSS9011-1-5 IP36	2	0.4%	2892.60
MILAN	2	0.4%	3657.96
N44	2	0.4%	3506.84
ND 801	2	0.4%	3114.80
OK03716W	2	0.4%	3506.84
OK94P455	2	0.4%	3506.84
PJN	2	0.4%	3410.47
RWA-Dn7 1BL.1RS	2	0.4%	3252.13
SAPI	2	0.4%	3559.15
SCAB-7	2	0.4%	3752.35
SD97380-2	2	0.4%	3197.50
SELYANKA	2	0.4%	3272.32
SERI 82	2	0.4%	2850.24
TAM 109	2	0.4%	2962.55
TEAL	2	0.4%	3559.15
TNMU	2	0.4%	2828.89
03CS234	2	0.4%	2129.23
97T1018	2	0.4%	2943.06
ABI 86 414	2	0.4%	3755.94
Arap	2	0.4%	2692.46
BATAVIA	2	0.4%	3457.96
BAU	2	0.4%	3397.72
BUC	2	0.4%	3828.38
C80.1	2	0.4%	3457.96
CIMMYT E95Syn4152-27	2	0.4%	3138.35
DESCONOCIDO	2	0.4%	2565.71
DIEBRE	2	0.4%	1951.33
FANG60	2	0.4%	1591.79
FL931339AS	2	0.4%	3418.06
FLORIDA 304	2	0.4%	3688.77
G980039	2	0.4%	2914.92
HUI	2	0.4%	3559.15
KAKATSI 'S'	2	0.4%	3626.33
TX00A0580	2	0.4%	2451.58
TX01A7340	2	0.4%	3234.68
TX01M5008	2	0.4%	2837.13
TX01U2699	2	0.4%	2636.99
TX02D6222	2	0.4%	2996.62
TX02V7525	2	0.4%	3519.60
TX04A001008	2	0.4%	3906.11
TX04M410139	2	0.4%	2943.06

TX04V076015	2	0.4%	3688.77
TX81V6582	2	0.4%	2565.71
TX86A8072	2	0.4%	3434.20
TX87A6763	2	0.4%	3906.11
TX88A6848	2	0.4%	3906.11
TX88A6880	2	0.4%	3485.78
TX93V4315	2	0.4%	3906.11
TX93V5723	2	0.4%	3234.68
TX94D7091	2	0.4%	3488.04
TX95V5314	2	0.4%	3262.96
TX96V2427	2	0.4%	2943.06
TX96V2627	2	0.4%	3488.04
TX97A0122	2	0.4%	3067.96
TX97V1613	2	0.4%	3202.48
TX98D1158	2	0.4%	2248.68
TX98U8618	2	0.4%	2892.60
TX99U8544	2	0.4%	2835.21
TXGH10440	2	0.4%	3010.75
VEE	2	0.4%	3410.47
VORONA	2	0.4%	3396.41
W03-20	2	0.4%	3594.93
X01A369	2	0.4%	2276.70
X01A383	2	0.4%	2730.53
X05A569	2	0.4%	3272.32
X05A584	2	0.4%	3252.13
X05A650	2	0.4%	3114.80
X84W063-9-39-2	2	0.4%	3755.94
KS03HW157-1	1	0.2%	2954.08
KS950811-5-1	1	0.2%	3505.49
KS96HW10-3	1	0.2%	3627.84
KS96WGRC39	1	0.2%	3421.01
KS970274	1	0.2%	3153.19
KS980191	1	0.2%	3408.08
KS990160	1	0.2%	3567.69
KSS9011-1-14 IP45	1	0.2%	3082.10
KSS9011-1-4 IP35	1	0.2%	2649.96
KSS9011-1-45 IP76	1	0.2%	3759.11
KSS9011-1-50 IP81	1	0.2%	2880.55
L92283C64-1	1	0.2%	2569.79
Largo	1	0.2%	2558.90
LOCKETT	1	0.2%	2206.05

LR42	1	0.2%	3351.40
Mediterranean	1	0.2%	2687.80
MINO	1	0.2%	3421.46
MTRWA92.155	1	0.2%	3176.70
MVC324-96	1	0.2%	3481.81
MVC327-96	1	0.2%	3759.24
N87V106	1	0.2%	2720.28
NAI80	1	0.2%	4099.12
ND 800	1	0.2%	3228.07
Nebraska 60	1	0.2%	2687.80
Norin 10	1	0.2%	2687.80
NORM	1	0.2%	3191.55
NW01L2019	1	0.2%	3131.18
NWX008106	1	0.2%	2119.99
OCW00M618S-1B	1	0.2%	3663.54
OCW00S047S-3B	1	0.2%	3153.19
OK Bullet	1	0.2%	3567.69
OK02232	1	0.2%	3249.95
OK02518W	1	0.2%	3567.69
OK04215	1	0.2%	3481.81
OK05128	1	0.2%	3650.11
OK91724	1	0.2%	3249.95
OK93P634	1	0.2%	3176.70
OK95G703-98-61416	1	0.2%	2673.59
OK98135	1	0.2%	3592.22
OLA OK03230	1	0.2%	3176.70
ORO BLANCO	1	0.2%	3481.81
Overly	1	0.2%	2649.96
OVL	1	0.2%	3374.47
PEWIT1	1	0.2%	2973.41
PF85487	1	0.2%	3533.02
PI 595757	1	0.2%	2558.90
PI137739	1	0.2%	3374.47
Pt7219	1	0.2%	3533.02
RAYON	1	0.2%	3481.81
SD97W604-1	1	0.2%	2669.60
SD-SWGP5	1	0.2%	3481.81
SHA7	1	0.2%	3176.70
Star derived	1	0.2%	2405.19
T-119	1	0.2%	2581.38
TA2460	1	0.2%	2249.36

TAM 211	1	0.2%	3125.25
TAM 302	1	0.2%	3674.00
TOMAHAWK	1	0.2%	3509.88
TRAP	1	0.2%	3759.24
TTCC58	1	0.2%	3394.84
02SR811	1	0.2%	2732.50
1233	1	0.2%	2634.47
2158	1	0.2%	3592.22
2163	1	0.2%	3913.19
2180	1	0.2%	3249.95
2180 K	1	0.2%	3913.19
97T1154	1	0.2%	3138.72
AE.SQ.205	1	0.2%	4099.12
AE.SQUARROSA	1	0.2%	3125.25
ALD	1	0.2%	3533.02
ALTAR 84	1	0.2%	3125.25
Amigo	1	0.2%	2558.90
AP01T3131	1	0.2%	3497.77
AP04T W1318	1	0.2%	3619.37
AP04T W9819	1	0.2%	3421.46
ASP	1	0.2%	3403.91
B1551W	1	0.2%	3674.00
BABAX	1	0.2%	3351.40
BAV92	1	0.2%	3125.25
BC41254-1-8-1-1	1	0.2%	3592.76
Bison	1	0.2%	2687.80
BJY	1	0.2%	3533.02
BLT	1	0.2%	3403.91
Briggs	1	0.2%	3396.99
BULK SELN	1	0.2%	3466.82
CBRD	1	0.2%	3533.02
CEP75234	1	0.2%	3533.02
CEP75630	1	0.2%	3533.02
CI 15324	1	0.2%	2687.80
CIMMYT E2Syn4153-24	1	0.2%	3049.11
CIMMYT E95Syn4152-14	1	0.2%	3144.88
CIMMYT E95Syn4152-30	1	0.2%	3246.21
CIMMYT E95Syn4152-37	1	0.2%	3015.67
CIMMYT E95Syn4152-55	1	0.2%	2647.23
CIMMYT E95Syn4152-70	1	0.2%	3226.79
CIMMYT E95Syn4152-8	1	0.2%	3379.78

CIMMYT E95Syn4152-83	1	0.2%	3293.36
CIMMYT-53	1	0.2%	3592.22
Cisco	1	0.2%	3164.11
CO970943	1	0.2%	2474.72
CO995080	1	0.2%	3462.48
CROC 1	1	0.2%	4099.12
CRR OK01325	1	0.2%	2249.36
CSM	1	0.2%	2886.08
CTY	1	0.2%	2249.36
CUSTER	1	0.2%	2680.43
DH432.89.3	1	0.2%	2344.81
DUSTER	1	0.2%	4099.12
F59	1	0.2%	4099.12
FM3	1	0.2%	2302.73
FREEDOM	1	0.2%	3509.88
G001784	1	0.2%	3860.15
G980172	1	0.2%	2322.15
G990191	1	0.2%	3570.89
GRANGER	1	0.2%	3080.05
GUYMON	1	0.2%	3403.91
HAHN	1	0.2%	3463.40
HBG0358	1	0.2%	2879.46
Hickok	1	0.2%	2498.33
HN7	1	0.2%	4099.12
Hope	1	0.2%	2687.80
HUW234+LR34	1	0.2%	3759.24
HV9W96-138R	1	0.2%	3674.00
HV9W99-558	1	0.2%	3509.88
HVA114	1	0.2%	3913.19
HXL7573	1	0.2%	3249.95
ITD	1	0.2%	3481.81
JAG	1	0.2%	3913.19
JGR 8W	1	0.2%	3914.26
KAMBI	1	0.2%	3913.19
KASORO 3	1	0.2%	2249.36
KB7	1	0.2%	1589.98
KM 1022-2-90	1	0.2%	2947.79
KS00HW183	1	0.2%	3457.93
KS01514	1	0.2%	3799.48
KS01HW152-6	1	0.2%	2880.55
TX00D1256	1	0.2%	2767.27

TX01A0174	1	0.2%	2923.70
TX01D3332	1	0.2%	2580.50
TX01U2503	1	0.2%	2175.01
TX01U2543	1	0.2%	2597.67
TX01V5425	1	0.2%	3268.17
TX01V5639	1	0.2%	2573.06
TX01V5722	1	0.2%	3546.37
TX01V5838	1	0.2%	3371.67
TX01V6016	1	0.2%	3500.65
TX01V6219	1	0.2%	2453.26
TX02A0341	1	0.2%	3687.26
TX02D5275	1	0.2%	3282.27
TX02D6249	1	0.2%	2626.30
TX02V7418	1	0.2%	2672.58
TX02V7438	1	0.2%	2626.30
TX03A0044	1	0.2%	3228.07
TX03A0121	1	0.2%	3783.62
TX03A0148	1	0.2%	3894.66
TX03A0182	1	0.2%	2984.55
TX03A0382	1	0.2%	2896.61
TX03A0563	1	0.2%	3008.20
TX03M1179	1	0.2%	3138.72
TX03M1214	1	0.2%	2590.28
TX03V72065	1	0.2%	3590.65
TX03V73097	1	0.2%	3612.65
TX03V74043	1	0.2%	3080.05
TX03V75096	1	0.2%	3078.31
TX04A001795	1	0.2%	3403.36
TX04A001830	1	0.2%	3918.48
TX04M410067	1	0.2%	3897.95
TX04M410082	1	0.2%	2961.10
TX04M410127	1	0.2%	3304.23
TX04M410145	1	0.2%	3138.72
TX04M410283	1	0.2%	3553.48
TX04V071069	1	0.2%	2947.79
TX04V073035	1	0.2%	3191.55
TX65A1682	1	0.2%	2687.80
TX84V1307	1	0.2%	3663.54
TX84V1317	1	0.2%	2498.33
TX85V1326	1	0.2%	2498.33
TX86V1405	1	0.2%	3592.76

TX87V1613	1	0.2%	2410.13
TX90V6313	1	0.2%	3592.76
TX91D6913	1	0.2%	3674.00
TX93D2385	1	0.2%	3897.95
TX94D4360	1	0.2%	3191.55
TX94V2140	1	0.2%	2306.26
TX94V3724	1	0.2%	3592.76
TX96D2240	1	0.2%	3294.98
TX96V7234	1	0.2%	1589.98
TX97A0169	1	0.2%	2697.40
TX97V3006	1	0.2%	3870.43
TX98D1073	1	0.2%	2673.59
TX98U8184	1	0.2%	2709.95
TX98V3620	1	0.2%	2720.28
TX99A0136	1	0.2%	2613.46
TX99A0248-2	1	0.2%	3806.98
TX99A0383-2	1	0.2%	2620.85
TX99A6030	1	0.2%	2680.43
TX99D3462	1	0.2%	2140.01
TX99D4572	1	0.2%	2096.38
TX99V3033	1	0.2%	2999.21
TX99V3034	1	0.2%	2599.68
TXGH12588-105	1	0.2%	2558.90
U4551B-R11-2R-1	1	0.2%	3530.40
VEE#6	1	0.2%	3403.91
VERDE	1	0.2%	3897.95
W 97-234	1	0.2%	2581.38
W1062A	1	0.2%	3913.19
W3416	1	0.2%	3913.19
W95-301	1	0.2%	3138.72
W97-234	1	0.2%	3783.62
W99-331	1	0.2%	1971.51
WHEATEAR	1	0.2%	3153.19
WI89-189-14	1	0.2%	3783.62
X01A358	1	0.2%	2306.26
X05A452	1	0.2%	3251.22
X05A462	1	0.2%	3550.19
X05A463	1	0.2%	3385.52
X05A474	1	0.2%	2961.10
X05A486	1	0.2%	3553.48
X05A494	1	0.2%	3304.23

X05A498	1	0.2%	3138.72
X05A515	1	0.2%	3294.98
X05A524	1	0.2%	3309.79
X05A526	1	0.2%	3517.31
X05A539	1	0.2%	3078.31
X05A546	1	0.2%	2896.61
X05A548	1	0.2%	3860.15
X05A554	1	0.2%	3949.50
X05A556	1	0.2%	3530.40
X05A578	1	0.2%	3730.56
X05A579	1	0.2%	3783.62
X05A602	1	0.2%	3567.96
X05A608	1	0.2%	2959.88
X05A647	1	0.2%	3228.07
X05A657	1	0.2%	3080.05
X05A658	1	0.2%	3396.99
X05A699	1	0.2%	3463.40
X921084-C-8-2	1	0.2%	3759.24
YACO	1	0.2%	3153.19

Appendix IV SAS code used to analyze F_1 population for yield and its components

```
data GHF1;
input Plot Entry Name $ Rep HD Plt_pot Head_pot Tillers HT Seed_pot Seed_head
Yield_pot Yield_plt Seed_wt Awns $;
cards;
;
proc glm;
class rep entry;
model HD Head_pot Tillers HT Seed_head Yield_pot Yield_plt Seed_wt = rep entry;
ODS Graphics off;
proc corr; var HD Head_pot Tillers HT Seed_head Yield_pot Yield_plt Seed_wt;
ODS Graphics off;
run;
```

Appendix V LSD calculation for grain yield per pot of F_1 population

Entry A	Entry B	Mean A	Mean B	B-A	Sig-nificance
TAM 111 x Sturdy 2K	TAM 113 x Sturdy 2K	0.8	6.4	5.60	*
TAM 111	TAM 113	0.53	6.1	5.57	*
TX10D2230	TAM 113 x Sturdy 2K	0.85	6.4	5.55	*
TAM 111 x Sturdy 2K	TAM 113 x TAM 305	0.8	5.97	5.17	*
TX10D2230	TAM 113 x TAM 305	0.85	5.97	5.12	*
TAM 111	TAM 112 x TAM 113	0.53	5.57	5.04	*
Sturdy 2K x TX10D2230	TAM 113	1.1	6.1	5.00	*
TAM 111	TAM 305	0.53	5.4	4.87	*
Sturdy 2K	TAM 113 x Sturdy 2K	1.6	6.4	4.80	*
TAM 111 x Sturdy 2K	TAM 112 x TAM 113	0.8	5.57	4.77	*
TX10D2230	TAM 112 x TAM 113	0.85	5.57	4.72	*
TAM 111	TAM 111 x TAM 305	0.53	5.23	4.70	*
TAM 111	TAM 112 x TAM 401	0.53	5.13	4.60	*
TAM 111	TAM 112 x TX11D3108	0.53	5.13	4.60	*
Sturdy 2K x TX10D2230	TAM 112 x TAM 113	1.1	5.57	4.47	*
TAM 112	TAM 113	1.7	6.1	4.40	*
TX10D2230	TAM 111 x TAM 305	0.85	5.23	4.38	*
Sturdy 2K	TAM 113 x TAM 305	1.6	5.97	4.37	*
TAM 111	TAM 111 x TAM 401	0.53	4.87	4.34	*
TAM 111 x Sturdy 2K	TAM 112 x TAM 401	0.8	5.13	4.33	*
TAM 111 x Sturdy 2K	TAM 112 x TX11D3108	0.8	5.13	4.33	*
TAM 111 x TX11D3108	TAM 113 x Sturdy 2K	2.1	6.4	4.30	*
Sturdy 2K x TX10D2230	TAM 305	1.1	5.4	4.30	*
TX10D2230	TAM 112 x TAM 401	0.85	5.13	4.28	*
TX10D2230	TAM 112 x TX11D3108	0.85	5.13	4.28	*
TAM 113 x TX10D2230	TAM 113	1.85	6.1	4.25	*
TAM 111	TAM 112 x TAM 305	0.53	4.77	4.24	*
TX11D3108	TAM 113 x TAM 305	1.8	5.97	4.17	*
Sturdy 2K x TX10D2230	TAM 111 x TAM 305	1.1	5.23	4.13	*

TAM 111 x Sturdy 2K	TAM 113 x TX11D3108	0.8	4.93	4.13	*
TX10D2230	TAM 113 x TX11D3108	0.85	4.93	4.08	*
TAM 111 x Sturdy 2K	TAM 113 x TAM 401	0.8	4.87	4.07	*
TAM 111	TAM 111 x TAM 112	0.53	4.6	4.07	*
TAM 112 x Sturdy 2K	TAM 113 x Sturdy 2K	2.35	6.4	4.05	*
TX10D2230	TAM 111 x TAM 401	0.85	4.87	4.02	*
TX10D2230	TAM 113 x TAM 401	0.85	4.87	4.02	*
TAM 111 x Sturdy 2K	TAM 305 x TX10D2230	0.8	4.8	4.00	*
Sturdy 2K	TAM 112 x TAM 113	1.6	5.57	3.97	*
TAM 111 x Sturdy 2K	TAM 112 x TAM 305	0.8	4.77	3.97	*
TX10D2230	TAM 112 x TAM 305	0.85	4.77	3.92	*
TAM 111 x Sturdy 2K	TAM 401 x TX11D3108	0.8	4.7	3.90	*
TAM 112	TAM 112 x TAM 113	1.7	5.57	3.87	*
TAM 111 x TX11D3108	TAM 113 x TAM 305	2.1	5.97	3.87	*
TAM 111	TAM 401	0.53	4.33	3.80	*
TX11D3108	TAM 112 x TAM 113	1.8	5.57	3.77	*
Sturdy 2K x TX10D2230	TAM 111 x TAM 401	1.1	4.87	3.77	*
TX10D2230	TAM 111 x TAM 112	0.85	4.6	3.75	*
TAM 112	TAM 305	1.7	5.4	3.70	*
Sturdy 2K x TX10D2230	TAM 112 x TAM 305	1.1	4.77	3.67	*
Sturdy 2K	TAM 111 x TAM 305	1.6	5.23	3.63	*
TAM 112 x TX10D2230	TAM 113 x Sturdy 2K	2.77	6.4	3.63	*
TAM 111 x Sturdy 2K	TAM 305 x TAM 401	0.8	4.43	3.63	*
TAM 112 x Sturdy 2K	TAM 113 x TAM 305	2.35	5.97	3.62	*
TAM 113 x TX10D2230	TAM 305	1.85	5.4	3.55	*
TAM 112	TAM 111 x TAM 305	1.7	5.23	3.53	*
Sturdy 2K	TAM 112 x TAM 401	1.6	5.13	3.53	*
Sturdy 2K	TAM 112 x TX11D3108	1.6	5.13	3.53	*
Sturdy 2K x TX10D2230	TAM 111 x TAM 112	1.1	4.6	3.50	*

TAM 111 x TX11D3108	TAM 112 x TAM 113	2.1	5.57	3.47	*
TX11D3108	TAM 111 x TAM 305	1.8	5.23	3.43	*
TAM 111 x TAM 113	TAM 113 x Sturdy 2K	2.97	6.4	3.43	*
TAM 112	TAM 112 x TAM 401	1.7	5.13	3.43	*
TAM 112	TAM 112 x TX11D3108	1.7	5.13	3.43	*
TX11D3108	TAM 112 x TAM 401	1.8	5.13	3.33	*
TX11D3108	TAM 112 x TX11D3108	1.8	5.13	3.33	*
Sturdy 2K	TAM 113 x TX11D3108	1.6	4.93	3.33	*
TAM 305 x TX11D3108	TAM 113	2.8	6.1	3.30	*
Sturdy 2K	TAM 111 x TAM 401	1.6	4.87	3.27	*
Sturdy 2K	TAM 113 x TAM 401	1.6	4.87	3.27	*
Sturdy 2K x TX10D2230	TAM 401	1.1	4.33	3.23	*
TAM 112 x TX10D2230	TAM 113 x TAM 305	2.77	5.97	3.20	*
TAM 112	TAM 111 x TAM 401	1.7	4.87	3.17	*
TAM 111 x Sturdy 2K	TAM 401 x Sturdy 2K	0.8	3.97	3.17	*
Sturdy 2K	TAM 112 x TAM 305	1.6	4.77	3.17	*
TAM 305 x Sturdy 2K	TAM 113	2.93	6.1	3.17	*
TX11D3108	TAM 113 x TX11D3108	1.8	4.93	3.13	*
TX11D3108	TAM 111 x TAM 401	1.8	4.87	3.07	*
TAM 111 x TX10D2230	TAM 113 x Sturdy 2K	3.33	6.4	3.07	*
TX11D3108	TAM 113 x TAM 401	1.8	4.87	3.07	*
TAM 112	TAM 112 x TAM 305	1.7	4.77	3.07	*
TAM 111 x TX11D3108	TAM 112 x TAM 401	2.1	5.13	3.03	*
TAM 111 x TX11D3108	TAM 112 x TX11D3108	2.1	5.13	3.03	*
Sturdy 2K	TAM 111 x TAM 112	1.6	4.6	3.00	*
TAM 111 x TAM 113	TAM 113 x TAM 305	2.97	5.97	3.00	*
TX11D3108	TAM 112 x TAM 305	1.8	4.77	2.97	*
TAM 113 x TX10D2230	TAM 305 x TX10D2230	1.85	4.8	2.95	*
TAM 112	TAM 111 x TAM 112	1.7	4.6	2.90	*

TAM 113 x TX10D2230	TAM 401 x TX11D3108	1.85	4.7	2.85	*
TAM 111 x TX11D3108	TAM 113 x TX11D3108	2.1	4.93	2.83	*
TX11D3108	TAM 111 x TAM 112	1.8	4.6	2.80	*
TAM 111	TAM 111 x TX10D2230	0.53	3.33	2.80	*
TX11D3108 x Sturdy 2K	TAM 113	3.3	6.1	2.80	*
TAM 111 x TX11D3108	TAM 113 x TAM 401	2.1	4.87	2.77	*
TAM 111 x TX11D3108	TAM 305 x TX10D2230	2.1	4.8	2.70	*
TAM 111 x TX11D3108	TAM 112 x TAM 305	2.1	4.77	2.67	*
TAM 111 x TX10D2230	TAM 113 x TAM 305	3.33	5.97	2.64	*
TAM 112	TAM 401	1.7	4.33	2.63	*
TAM 305 x TX11D3108	TAM 305	2.8	5.4	2.60	*
TAM 111 x TAM 113	TAM 112 x TAM 113	2.97	5.57	2.60	*
TAM 111 x TX11D3108	TAM 401 x TX11D3108	2.1	4.7	2.60	*
TAM 112 x Sturdy 2K	TAM 113 x TX11D3108	2.35	4.93	2.58	*
TAM 113 x TX10D2230	TAM 305 x TAM 401	1.85	4.43	2.58	*
TX11D3108 x TX10D2230	TAM 113	3.53	6.1	2.57	*
TAM 111 x Sturdy 2K	TAM 111 x TX10D2230	0.8	3.33	2.53	*
TAM 112 x Sturdy 2K	TAM 113 x TAM 401	2.35	4.87	2.52	*
TX10D2230	TAM 111 x TX10D2230	0.85	3.33	2.48	*
TAM 113 x TX10D2230	TAM 401	1.85	4.33	2.48	*
TAM 305 x Sturdy 2K	TAM 305	2.93	5.4	2.47	*
TAM 112 x Sturdy 2K	TAM 305 x TX10D2230	2.35	4.8	2.45	*
TAM 111	TAM 111 x TAM 113	0.53	2.97	2.44	*
TAM 113 x TX10D2230	TAM 401 x TX10D2230	1.85	4.27	2.42	*

TAM 112 x Sturdy 2K	TAM 401 x TX11D3108	2.35	4.7	2.35	*
TAM 111 x TX11D3108	TAM 305 x TAM 401	2.1	4.43	2.33	*
TAM 111 x TAM 113	TAM 111 x TAM 305	2.97	5.23	2.26	*
TAM 111 x TX10D2230	TAM 112 x TAM 113	3.33	5.57	2.24	*
Sturdy 2K x TX10D2230	TAM 111 x TX10D2230	1.1	3.33	2.23	*
TAM 111 x TAM 113	TAM 112 x TAM 401	2.97	5.13	2.16	*
TAM 111 x TAM 113	TAM 112 x TX11D3108	2.97	5.13	2.16	*
TAM 112 x TX10D2230	TAM 113 x TX11D3108	2.77	4.93	2.16	*
TAM 111 x Sturdy 2K	TAM 305 x Sturdy 2K	0.8	2.93	2.13	*
TAM 401 x Sturdy 2K	TAM 113	3.97	6.1	2.13	*
TX10D2230	TAM 111 x TAM 113	0.85	2.97	2.12	*
TAM 113 x TX10D2230	TAM 401 x Sturdy 2K	1.85	3.97	2.12	*
TX11D3108 x Sturdy 2K	TAM 305	3.3	5.4	2.10	*
TAM 112 x TX10D2230	TAM 113 x TAM 401	2.77	4.87	2.10	*
TAM 112 x Sturdy 2K	TAM 305 x TAM 401	2.35	4.43	2.08	*
TX11D3108 x TX10D2230	TAM 112 x TAM 113	3.53	5.57	2.04	*
TAM 112 x TX10D2230	TAM 305 x TX10D2230	2.77	4.8	2.03	*
TAM 305 x TX11D3108	TAM 305 x TX10D2230	2.8	4.8	2.00	*
TAM 111 x Sturdy 2K	TAM 305 x TX11D3108	0.8	2.8	2.00	*
TAM 111 x Sturdy 2K	TAM 112 x TX10D2230	0.8	2.77	1.97	*
TAM 111 x TAM 113	TAM 113 x TX11D3108	2.97	4.93	1.96	*
TX11D3108 x Sturdy 2K	TAM 111 x TAM 305	3.3	5.23	1.93	*
TAM 112 x TX10D2230	TAM 401 x TX11D3108	2.77	4.7	1.93	*

TX10D2230	TAM 112 x TX10D2230	0.85	2.77	1.92	*
TAM 112 x Sturdy 2K	TAM 401 x TX10D2230	2.35	4.27	1.92	*
TAM 305 x TX11D3108	TAM 401 x TX11D3108	2.8	4.7	1.90	*
TAM 111 x TAM 113	TAM 111 x TAM 401	2.97	4.87	1.90	*
TAM 111 x TAM 113	TAM 113 x TAM 401	2.97	4.87	1.90	*
TX11D3108 x TX10D2230	TAM 305	3.53	5.4	1.87	*
Sturdy 2K x TX10D2230	TAM 111 x TAM 113	1.1	2.97	1.87	*
TAM 305 x Sturdy 2K	TAM 305 x TX10D2230	2.93	4.8	1.87	*
TAM 401 x TX10D2230	TAM 113	4.27	6.1	1.83	*
TAM 111 x TAM 112	TAM 113 x Sturdy 2K	4.6	6.4	1.80	*
TAM 305 x TX11D3108	TAM 111 x TAM 112	2.8	4.6	1.80	*
TAM 111 x TX10D2230	TAM 112 x TAM 401	3.33	5.13	1.80	*
TAM 111 x TX10D2230	TAM 112 x TX11D3108	3.33	5.13	1.80	*
TAM 111 x TAM 113	TAM 112 x TAM 305	2.97	4.77	1.80	*
TAM 305 x Sturdy 2K	TAM 401 x TX11D3108	2.93	4.7	1.77	*
Sturdy 2K	TAM 111 x TX10D2230	1.6	3.33	1.73	*
TX11D3108 x TX10D2230	TAM 111 x TAM 305	3.53	5.23	1.70	*
TAM 113 x TX10D2230	TX11D3108 x TX10D2230	1.85	3.53	1.68	NS
TAM 305 x TAM 401	TAM 113	4.43	6.1	1.67	*
TAM 305 x Sturdy 2K	TAM 111 x TAM 112	2.93	4.6	1.67	*
TAM 112 x TX10D2230	TAM 305 x TAM 401	2.77	4.43	1.66	*
TAM 401	TAM 113 x TAM 305	4.33	5.97	1.64	*
TAM 112 x TAM 305	TAM 113 x Sturdy 2K	4.77	6.4	1.63	*

TAM 112	TAM 111 x TX10D2230	1.7	3.33	1.63	*
TAM 112 x Sturdy 2K	TAM 401 x Sturdy 2K	2.35	3.97	1.62	NS
TAM 111 x TX10D2230	TAM 113 x TX11D3108	3.33	4.93	1.60	*
TX11D3108 x Sturdy 2K	TAM 111 x TAM 401	3.3	4.87	1.57	*
TAM 111	TAM 111 x TX11D3108	0.53	2.1	1.57	*
TAM 111 x Sturdy 2K	TAM 112 x Sturdy 2K	0.8	2.35	1.55	NS
TAM 111 x TX10D2230	TAM 113 x TAM 401	3.33	4.87	1.54	*
TAM 111 x TAM 401	TAM 113 x Sturdy 2K	4.87	6.4	1.53	*
TAM 113 x TAM 401	TAM 113 x Sturdy 2K	4.87	6.4	1.53	*
TAM 305 x TX11D3108	TAM 401	2.8	4.33	1.53	*
TX11D3108	TAM 111 x TX10D2230	1.8	3.33	1.53	NS
TX10D2230	TAM 112 x Sturdy 2K	0.85	2.35	1.50	*
TAM 112 x TX10D2230	TAM 401 x TX10D2230	2.77	4.27	1.50	*
TAM 113 x TX11D3108	TAM 113 x Sturdy 2K	4.93	6.4	1.47	*
TAM 111 x TX10D2230	TAM 305 x TX10D2230	3.33	4.8	1.47	*
TAM 305 x TX11D3108	TAM 401 x TX10D2230	2.8	4.27	1.47	*
TAM 111 x TAM 113	TAM 305 x TAM 401	2.97	4.43	1.46	NS
TAM 113 x TX10D2230	TX11D3108 x Sturdy 2K	1.85	3.3	1.45	NS
TAM 111 x TX10D2230	TAM 112 x TAM 305	3.33	4.77	1.44	NS
TAM 401 x Sturdy 2K	TAM 305	3.97	5.4	1.43	NS
TAM 305 x Sturdy 2K	TAM 401	2.93	4.33	1.40	NS
TAM 401 x TX11D3108	TAM 113	4.7	6.1	1.40	NS
Sturdy 2K	TAM 111 x TAM 113	1.6	2.97	1.37	NS

TAM 111 x TAM 112	TAM 113 x TAM 305	4.6	5.97	1.37	NS
TAM 111 x TX10D2230	TAM 401 x TX11D3108	3.33	4.7	1.37	NS
TX11D3108 x TX10D2230	TAM 111 x TAM 401	3.53	4.87	1.34	NS
TAM 305 x Sturdy 2K	TAM 401 x TX10D2230	2.93	4.27	1.34	NS
TX11D3108 x Sturdy 2K	TAM 111 x TAM 112	3.3	4.6	1.30	NS
TAM 305 x TX10D2230	TAM 113	4.8	6.1	1.30	NS
TAM 112 x TAM 401	TAM 113 x Sturdy 2K	5.13	6.4	1.27	NS
TAM 112 x TX11D3108	TAM 113 x Sturdy 2K	5.13	6.4	1.27	NS
TAM 112	TAM 111 x TAM 113	1.7	2.97	1.27	NS
TAM 111	TX11D3108	0.53	1.8	1.27	NS
TAM 401 x Sturdy 2K	TAM 111 x TAM 305	3.97	5.23	1.26	NS
TX10D2230	TAM 111 x TX11D3108	0.85	2.1	1.25	NS
TAM 401	TAM 112 x TAM 113	4.33	5.57	1.24	NS
TAM 111 x TX11D3108	TAM 111 x TX10D2230	2.1	3.33	1.23	NS
TAM 113 x TAM 401	TAM 113	4.87	6.1	1.23	NS
TAM 112 x TAM 305	TAM 113 x TAM 305	4.77	5.97	1.20	NS
TAM 112 x TX10D2230	TAM 401 x Sturdy 2K	2.77	3.97	1.20	NS
TAM 112 x Sturdy 2K	TX11D3108 x TX10D2230	2.35	3.53	1.18	NS
TAM 305 x TX11D3108	TAM 401 x Sturdy 2K	2.8	3.97	1.17	NS
TX11D3108	TAM 111 x TAM 113	1.8	2.97	1.17	NS
TAM 111	TAM 112	0.53	1.7	1.17	NS
Sturdy 2K	TAM 112 x TX10D2230	1.6	2.77	1.17	NS
TAM 113 x TX11D3108	TAM 113	4.93	6.1	1.17	NS
TAM 111 x TAM 305	TAM 113 x Sturdy 2K	5.23	6.4	1.17	NS
TAM 401 x TX10D2230	TAM 305	4.27	5.4	1.13	NS

TAM 111 x TAM 401	TAM 113 x TAM 305	4.87	5.97	1.10	NS
TAM 111 x TX10D2230	TAM 305 x TAM 401	3.33	4.43	1.10	NS
TAM 113 x TX10D2230	TAM 305 x Sturdy 2K	1.85	2.93	1.08	NS
TAM 111	Sturdy 2K	0.53	1.6	1.07	NS
TX11D3108 x TX10D2230	TAM 111 x TAM 112	3.53	4.6	1.07	NS
TAM 111 x Sturdy 2K	TAM 113 x TX10D2230	0.8	1.85	1.05	NS
TAM 305 x Sturdy 2K	TAM 401 x Sturdy 2K	2.93	3.97	1.04	NS
TX11D3108 x Sturdy 2K	TAM 401	3.3	4.33	1.03	NS
Sturdy 2K x TX10D2230	TAM 111 x TX11D3108	1.1	2.1	1.00	NS
TX10D2230	TAM 113 x TX10D2230	0.85	1.85	1.00	NS
TAM 111 x TAM 112	TAM 112 x TAM 113	4.6	5.57	0.97	NS
TAM 305 x TAM 401	TAM 305	4.43	5.4	0.97	NS
TX11D3108	TAM 112 x TX10D2230	1.8	2.77	0.97	NS
TAM 401 x TX10D2230	TAM 111 x TAM 305	4.27	5.23	0.96	NS
TAM 113 x TX10D2230	TAM 305 x TX11D3108	1.85	2.8	0.95	NS
TAM 112 x Sturdy 2K	TX11D3108 x Sturdy 2K	2.35	3.3	0.95	NS
TAM 111 x TX10D2230	TAM 401 x TX10D2230	3.33	4.27	0.94	NS
TAM 401	TAM 111 x TAM 305	4.33	5.23	0.90	NS
TAM 401 x Sturdy 2K	TAM 111 x TAM 401	3.97	4.87	0.90	NS
TAM 112 x TAM 401	TAM 113 x TAM 305	5.13	5.97	0.84	NS
TAM 112 x TX11D3108	TAM 113 x TAM 305	5.13	5.97	0.84	NS
TAM 112 x TAM 113	TAM 113 x Sturdy 2K	5.57	6.4	0.83	NS
TAM 111 x TX11D3108	TAM 305 x Sturdy 2K	2.1	2.93	0.83	NS

TX11D3108 x TX10D2230	TAM 401	3.53	4.33	0.80	NS
TAM 401	TAM 112 x TAM 401	4.33	5.13	0.80	NS
TAM 401	TAM 112 x TX11D3108	4.33	5.13	0.80	NS
TAM 112 x TX10D2230	TX11D3108 x TX10D2230	2.77	3.53	0.76	NS
Sturdy 2K	TAM 112 x Sturdy 2K	1.6	2.35	0.75	NS
TAM 111 x TAM 305	TAM 113 x TAM 305	5.23	5.97	0.74	NS
TAM 305 x TX11D3108	TX11D3108 x TX10D2230	2.8	3.53	0.73	NS
TAM 111 x TAM 401	TAM 112 x TAM 113	4.87	5.57	0.70	NS
TAM 401 x TX11D3108	TAM 305	4.7	5.4	0.70	NS
Sturdy 2K x TX10D2230	TX11D3108	1.1	1.8	0.70	NS
TAM 111 x TX11D3108	TAM 305 x TX11D3108	2.1	2.8	0.70	NS
TAM 111 x TX11D3108	TAM 112 x TX10D2230	2.1	2.77	0.67	NS
TAM 112	TAM 112 x Sturdy 2K	1.7	2.35	0.65	NS
TAM 111 x TX10D2230	TAM 401 x Sturdy 2K	3.33	3.97	0.64	NS
TAM 111 x TAM 112	TAM 111 x TAM 305	4.6	5.23	0.63	NS
TAM 401 x Sturdy 2K	TAM 111 x TAM 112	3.97	4.6	0.63	NS
TAM 401 x TX10D2230	TAM 111 x TAM 401	4.27	4.87	0.60	NS
TAM 305 x TX10D2230	TAM 305	4.8	5.4	0.60	NS
Sturdy 2K x TX10D2230	TAM 112	1.1	1.7	0.60	NS
TAM 305 x Sturdy 2K	TX11D3108 x TX10D2230	2.93	3.53	0.60	NS
TAM 112 x Sturdy 2K	TAM 305 x Sturdy 2K	2.35	2.93	0.58	NS
TAM 305	TAM 113 x TAM 305	5.4	5.97	0.57	NS
TX11D3108	TAM 112 x Sturdy 2K	1.8	2.35	0.55	NS
TAM 401	TAM 111 x TAM 401	4.33	4.87	0.54	NS
TAM 401	TAM 113 x TAM 401	4.33	4.87	0.54	NS
TAM 401 x TX11D3108	TAM 111 x TAM 305	4.7	5.23	0.53	NS

TAM 111 x TAM 112	TAM 112 x TAM 401	4.6	5.13	0.53	NS
TAM 111 x TAM 112	TAM 112 x TX11D3108	4.6	5.13	0.53	NS
TAM 113 x TAM 401	TAM 305	4.87	5.4	0.53	NS
TAM 112 x TX10D2230	TX11D3108 x Sturdy 2K	2.77	3.3	0.53	NS
Sturdy 2K x TX10D2230	Sturdy 2K	1.1	1.6	0.50	NS
Sturdy 2K	TAM 111 x TX11D3108	1.6	2.1	0.50	NS
TAM 305 x TX11D3108	TX11D3108 x Sturdy 2K	2.8	3.3	0.50	NS
TAM 113 x TX11D3108	TAM 305	4.93	5.4	0.47	NS
TAM 112 x Sturdy 2K	TAM 305 x TX11D3108	2.35	2.8	0.45	NS
TAM 401	TAM 112 x TAM 305	4.33	4.77	0.44	NS
TAM 305 x TX10D2230	TAM 111 x TAM 305	4.8	5.23	0.43	NS
TAM 113 x TAM 305	TAM 113 x Sturdy 2K	5.97	6.4	0.43	NS
TAM 112 x Sturdy 2K	TAM 112 x TX10D2230	2.35	2.77	0.42	NS
TAM 112	TAM 111 x TX11D3108	1.7	2.1	0.40	NS
TAM 112 x TAM 113	TAM 113 x TAM 305	5.57	5.97	0.40	NS
TAM 305 x TAM 401	TAM 305 x TX10D2230	4.43	4.8	0.37	NS
TAM 305 x Sturdy 2K	TX11D3108 x Sturdy 2K	2.93	3.3	0.37	NS
TAM 112 x TAM 305	TAM 112 x TAM 401	4.77	5.13	0.36	NS
TAM 112 x TAM 305	TAM 112 x TX11D3108	4.77	5.13	0.36	NS
TAM 111 x TAM 113	TAM 111 x TX10D2230	2.97	3.33	0.36	NS
TAM 401 x Sturdy 2K	TAM 401	3.97	4.33	0.36	NS
TAM 111 x TAM 305	TAM 112 x TAM 113	5.23	5.57	0.34	NS
TAM 401 x TX10D2230	TAM 111 x TAM 112	4.27	4.6	0.33	NS

TAM 111 x TAM 112	TAM 113 x TX11D3108	4.6	4.93	0.33	NS
TAM 111	TX10D2230	0.53	0.85	0.32	NS
TX11D3108	TAM 111 x TX11D3108	1.8	2.1	0.30	NS
TAM 401 x Sturdy 2K	TAM 401 x TX10D2230	3.97	4.27	0.30	NS
TAM 111 x TAM 112	TAM 111 x TAM 401	4.6	4.87	0.27	NS
TAM 111 x TAM 112	TAM 113 x TAM 401	4.6	4.87	0.27	NS
TAM 305 x TAM 401	TAM 401 x TX11D3108	4.43	4.7	0.27	NS
TAM 111	TAM 111 x Sturdy 2K	0.53	0.8	0.27	NS
TAM 401	TAM 111 x TAM 112	4.33	4.6	0.27	NS
TAM 111 x TAM 401	TAM 112 x TAM 401	4.87	5.13	0.26	NS
TAM 111 x TAM 401	TAM 112 x TX11D3108	4.87	5.13	0.26	NS
TAM 111 x TX11D3108	TAM 112 x Sturdy 2K	2.1	2.35	0.25	NS
TX11D3108 x Sturdy 2K	TX11D3108 x TX10D2230	3.3	3.53	0.23	NS
TAM 401 x TX11D3108	TAM 111 x TAM 401	4.7	4.87	0.17	NS
TAM 305	TAM 112 x TAM 113	5.4	5.57	0.17	NS
TAM 111 x TAM 112	TAM 112 x TAM 305	4.6	4.77	0.17	NS
TAM 112 x TAM 305	TAM 113 x TX11D3108	4.77	4.93	0.16	NS
TAM 112 x TX10D2230	TAM 305 x Sturdy 2K	2.77	2.93	0.16	NS
TAM 305 x TX11D3108	TAM 305 x Sturdy 2K	2.8	2.93	0.13	NS
TAM 113 x TAM 305	TAM 113	5.97	6.1	0.13	NS
TAM 112 x TAM 305	TAM 113 x TAM 401	4.77	4.87	0.10	NS
TAM 112	TX11D3108	1.7	1.8	0.10	NS
TAM 401 x TX10D2230	TAM 401	4.27	4.33	0.06	NS
TAM 111 x TAM 401	TAM 113 x TX11D3108	4.87	4.93	0.06	NS
TAM 113 x TAM 401	TAM 113 x TX11D3108	4.87	4.93	0.06	NS

TAM 305 x Sturdy 2K	TAM 111 x TAM 113	2.93	2.97	0.04	NS
TX11D3108 x Sturdy 2K	TAM 111 x TX10D2230	3.3	3.33	0.03	NS
TAM 112 x TAM 305	TAM 305 x TX10D2230	4.77	4.8	0.03	NS
TAM 112 x TX10D2230	TAM 305 x TX11D3108	2.77	2.8	0.03	NS
TAM 112 x TAM 401	TAM 112 x TX11D3108	5.13	5.13	0.00	NS
TAM 111 x TAM 401	TAM 113 x TAM 401	4.87	4.87	0.00	NS
TX10D2230	TAM 111 x Sturdy 2K	0.85	0.8	-0.05	NS
TAM 113 x TX10D2230	TX11D3108	1.85	1.8	-0.05	NS
TAM 112 x TAM 305	TAM 401 x TX11D3108	4.77	4.7	-0.07	NS
TAM 111 x TAM 401	TAM 305 x TX10D2230	4.87	4.8	-0.07	NS
TAM 113 x TAM 401	TAM 305 x TX10D2230	4.87	4.8	-0.07	NS
TAM 305 x TAM 401	TAM 401	4.43	4.33	-0.10	NS
TAM 305 x TX10D2230	TAM 401 x TX11D3108	4.8	4.7	-0.10	NS
TAM 112	Sturdy 2K	1.7	1.6	-0.10	NS
TAM 401 x TX11D3108	TAM 111 x TAM 112	4.7	4.6	-0.10	NS
TAM 111 x TAM 401	TAM 112 x TAM 305	4.87	4.77	-0.10	NS
TAM 111 x TAM 305	TAM 112 x TAM 401	5.23	5.13	-0.10	NS
TAM 111 x TAM 305	TAM 112 x TX11D3108	5.23	5.13	-0.10	NS
TAM 113 x TX11D3108	TAM 305 x TX10D2230	4.93	4.8	-0.13	NS
TAM 113 x TX10D2230	TAM 112	1.85	1.7	-0.15	NS
TAM 305 x TAM 401	TAM 401 x TX10D2230	4.43	4.27	-0.16	NS
TAM 305	TAM 111 x TAM 305	5.4	5.23	-0.17	NS
TAM 111 x TAM 112	TAM 305 x TAM 401	4.6	4.43	-0.17	NS
TAM 113 x TAM 401	TAM 401 x TX11D3108	4.87	4.7	-0.17	NS

TAM 111 x TAM 113	TAM 305 x TX11D3108	2.97	2.8	-0.17	NS
TX11D3108 x TX10D2230	TAM 111 x TX10D2230	3.53	3.33	-0.20	NS
TX11D3108	Sturdy 2K	1.8	1.6	-0.20	NS
TAM 305 x TX10D2230	TAM 111 x TAM 112	4.8	4.6	-0.20	NS
TAM 111 x TAM 113	TAM 112 x TX10D2230	2.97	2.77	-0.20	NS
TAM 112 x TAM 401	TAM 113 x TX11D3108	5.13	4.93	-0.20	NS
TAM 112 x TX11D3108	TAM 113 x TX11D3108	5.13	4.93	-0.20	NS
TAM 113 x TX11D3108	TAM 401 x TX11D3108	4.93	4.7	-0.23	NS
TAM 113 x TX10D2230	Sturdy 2K	1.85	1.6	-0.25	NS
TAM 111 x TX11D3108	TAM 113 x TX10D2230	2.1	1.85	-0.25	NS
Sturdy 2K x TX10D2230	TX10D2230	1.1	0.85	-0.25	NS
TAM 112 x TAM 401	TAM 113 x TAM 401	5.13	4.87	-0.26	NS
TAM 112 x TX11D3108	TAM 113 x TAM 401	5.13	4.87	-0.26	NS
TAM 305	TAM 112 x TAM 401	5.4	5.13	-0.27	NS
TAM 305	TAM 112 x TX11D3108	5.4	5.13	-0.27	NS
Sturdy 2K x TX10D2230	TAM 111 x Sturdy 2K	1.1	0.8	-0.30	NS
TAM 113 x Sturdy 2K	TAM 113	6.4	6.1	-0.30	NS
TAM 111 x TAM 305	TAM 113 x TX11D3108	5.23	4.93	-0.30	NS
TX11D3108 x Sturdy 2K	TAM 111 x TAM 113	3.3	2.97	-0.33	NS
TAM 112 x TAM 401	TAM 305 x TX10D2230	5.13	4.8	-0.33	NS
TAM 112 x TX11D3108	TAM 305 x TX10D2230	5.13	4.8	-0.33	NS
TAM 112 x TAM 305	TAM 305 x TAM 401	4.77	4.43	-0.34	NS
TAM 111 x TAM 305	TAM 111 x TAM 401	5.23	4.87	-0.36	NS

TAM 111 x TAM 305	TAM 113 x TAM 401	5.23	4.87	-0.36	NS
TAM 401 x TX11D3108	TAM 401	4.7	4.33	-0.37	NS
TAM 111 x TX10D2230	TAM 305 x Sturdy 2K	3.33	2.93	-0.40	NS
TAM 112 x TAM 401	TAM 401 x TX11D3108	5.13	4.7	-0.43	NS
TAM 112 x TX11D3108	TAM 401 x TX11D3108	5.13	4.7	-0.43	NS
TAM 401 x TX11D3108	TAM 401 x TX10D2230	4.7	4.27	-0.43	NS
TAM 112 x TAM 113	TAM 112 x TAM 401	5.57	5.13	-0.44	NS
TAM 112 x TAM 113	TAM 112 x TX11D3108	5.57	5.13	-0.44	NS
TAM 111 x TAM 401	TAM 305 x TAM 401	4.87	4.43	-0.44	NS
TAM 113 x TAM 401	TAM 305 x TAM 401	4.87	4.43	-0.44	NS
TAM 401 x Sturdy 2K	TX11D3108 x TX10D2230	3.97	3.53	-0.44	NS
TAM 305 x TAM 401	TAM 401 x Sturdy 2K	4.43	3.97	-0.46	NS
TAM 111 x TAM 305	TAM 112 x TAM 305	5.23	4.77	-0.46	NS
TAM 305 x TX10D2230	TAM 401	4.8	4.33	-0.47	NS
TAM 112 x Sturdy 2K	TAM 113 x TX10D2230	2.35	1.85	-0.50	NS
TAM 113 x TX11D3108	TAM 305 x TAM 401	4.93	4.43	-0.50	NS
TAM 112 x TAM 305	TAM 401 x TX10D2230	4.77	4.27	-0.50	NS
TAM 113	TAM 112 x TAM 113	6.1	5.57	-0.53	NS
TAM 305	TAM 111 x TAM 401	5.4	4.87	-0.53	NS
TAM 111 x TX10D2230	TAM 305 x TX11D3108	3.33	2.8	-0.53	NS
TAM 305 x TX10D2230	TAM 401 x TX10D2230	4.8	4.27	-0.53	NS
TX11D3108 x TX10D2230	TAM 111 x TAM 113	3.53	2.97	-0.56	NS
TAM 111 x TX10D2230	TAM 112 x TX10D2230	3.33	2.77	-0.56	NS

Sturdy 2K x TX10D2230	TAM 111	1.1	0.53	-0.57	NS
TAM 113 x TX11D3108	TAM 401	4.93	4.33	-0.60	NS
TAM 113 x TAM 401	TAM 401 x TX10D2230	4.87	4.27	-0.60	NS
TAM 111 x TAM 113	TAM 112 x Sturdy 2K	2.97	2.35	-0.62	NS
TAM 305	TAM 112 x TAM 305	5.4	4.77	-0.63	NS
TAM 112 x TAM 113	TAM 113 x TX11D3108	5.57	4.93	-0.64	NS
TAM 113 x TX11D3108	TAM 401 x TX10D2230	4.93	4.27	-0.66	NS
TAM 401 x Sturdy 2K	TX11D3108 x Sturdy 2K	3.97	3.3	-0.67	NS
TAM 113	TAM 305	6.1	5.4	-0.70	NS
TAM 112 x TAM 113	TAM 113 x TAM 401	5.57	4.87	-0.70	NS
TAM 112 x TAM 401	TAM 305 x TAM 401	5.13	4.43	-0.70	NS
TAM 112 x TX11D3108	TAM 305 x TAM 401	5.13	4.43	-0.70	NS
TAM 401 x TX11D3108	TAM 401 x Sturdy 2K	4.7	3.97	-0.73	NS
TAM 401 x TX10D2230	TX11D3108 x TX10D2230	4.27	3.53	-0.74	NS
TAM 113 x TX10D2230	Sturdy 2K x TX10D2230	1.85	1.1	-0.75	NS
Sturdy 2K	TX10D2230	1.6	0.85	-0.75	NS
TAM 112 x TAM 113	TAM 305 x TX10D2230	5.57	4.8	-0.77	NS
TAM 112 x TAM 305	TAM 401 x Sturdy 2K	4.77	3.97	-0.80	NS
Sturdy 2K	TAM 111 x Sturdy 2K	1.6	0.8	-0.80	NS
TAM 305	TAM 111 x TAM 112	5.4	4.6	-0.80	NS
TAM 112 x TAM 113	TAM 112 x TAM 305	5.57	4.77	-0.80	NS
TAM 111 x TAM 305	TAM 305 x TAM 401	5.23	4.43	-0.80	NS
TAM 305 x TX10D2230	TAM 401 x Sturdy 2K	4.8	3.97	-0.83	NS
TAM 112	TX10D2230	1.7	0.85	-0.85	NS
TAM 112 x TAM 401	TAM 401 x TX10D2230	5.13	4.27	-0.86	NS

TAM 112 x TX11D3108	TAM 401 x TX10D2230	5.13	4.27	-0.86	NS
TAM 113	TAM 111 x TAM 305	6.1	5.23	-0.87	NS
TAM 111 x TAM 113	TAM 111 x TX11D3108	2.97	2.1	-0.87	NS
TAM 112 x TAM 113	TAM 401 x TX11D3108	5.57	4.7	-0.87	NS
TAM 112	TAM 111 x Sturdy 2K	1.7	0.8	-0.90	NS
TAM 113 x TAM 401	TAM 401 x Sturdy 2K	4.87	3.97	-0.90	NS
TAM 305 x TAM 401	TX11D3108 x TX10D2230	4.43	3.53	-0.90	NS
TAM 112 x TX10D2230	TAM 113 x TX10D2230	2.77	1.85	-0.92	NS
TX11D3108	TX10D2230	1.8	0.85	-0.95	NS
TAM 113 x TX11D3108	TAM 401 x Sturdy 2K	4.93	3.97	-0.96	NS
TAM 113	TAM 112 x TAM 401	6.1	5.13	-0.97	NS
TAM 113	TAM 112 x TX11D3108	6.1	5.13	-0.97	NS
TAM 401 x TX10D2230	TX11D3108 x Sturdy 2K	4.27	3.3	-0.97	NS
TAM 111 x TX10D2230	TAM 112 x Sturdy 2K	3.33	2.35	-0.98	NS
TAM 305 x TX11D3108	TX11D3108	2.8	1.8	-1.00	NS
TX11D3108	TAM 111 x Sturdy 2K	1.8	0.8	-1.00	NS
TAM 401 x Sturdy 2K	TAM 111 x TAM 113	3.97	2.97	-1.00	NS
TAM 401	TAM 111 x TX10D2230	4.33	3.33	-1.00	NS
TAM 113 x Sturdy 2K	TAM 305	6.4	5.4	-1.00	NS
TAM 113 x TAM 305	TAM 113 x TX11D3108	5.97	4.93	-1.04	NS
TAM 112 x TX10D2230	TAM 112	2.77	1.7	-1.07	NS
TAM 305	TAM 401	5.4	4.33	-1.07	NS
TAM 113 x TAM 305	TAM 113 x TAM 401	5.97	4.87	-1.10	NS
TAM 305 x TX11D3108	TAM 112	2.8	1.7	-1.10	NS
TAM 111 x TAM 113	TAM 113 x TX10D2230	2.97	1.85	-1.12	NS

TAM 305 x TAM 401	TX11D3108 x Sturdy 2K	4.43	3.3	-1.13	NS
TAM 305 x Sturdy 2K	TX11D3108	2.93	1.8	-1.13	NS
TAM 112 x TAM 113	TAM 305 x TAM 401	5.57	4.43	-1.14	NS
TAM 112 x TAM 401	TAM 401 x Sturdy 2K	5.13	3.97	-1.16	NS
TAM 112 x TX11D3108	TAM 401 x Sturdy 2K	5.13	3.97	-1.16	NS
TAM 113 x TAM 305	TAM 305 x TX10D2230	5.97	4.8	-1.17	NS
TAM 401 x TX11D3108	TX11D3108 x TX10D2230	4.7	3.53	-1.17	NS
TAM 305 x TX11D3108	Sturdy 2K	2.8	1.6	-1.20	NS
TX11D3108 x Sturdy 2K	TAM 111 x TX11D3108	3.3	2.1	-1.20	NS
TAM 113	TAM 111 x TAM 401	6.1	4.87	-1.23	NS
TAM 305 x Sturdy 2K	TAM 112	2.93	1.7	-1.23	NS
TAM 112 x TAM 305	TX11D3108 x TX10D2230	4.77	3.53	-1.24	NS
TAM 112 x Sturdy 2K	Sturdy 2K x TX10D2230	2.35	1.1	-1.25	NS
TAM 111 x TAM 112	TAM 111 x TX10D2230	4.6	3.33	-1.27	NS
TAM 113 x TAM 305	TAM 401 x TX11D3108	5.97	4.7	-1.27	NS
TAM 305 x TX10D2230	TX11D3108 x TX10D2230	4.8	3.53	-1.27	NS
TAM 401 x TX10D2230	TAM 111 x TAM 113	4.27	2.97	-1.30	NS
TAM 111 x TX11D3108	TAM 111 x Sturdy 2K	2.1	0.8	-1.30	NS
TAM 112 x TAM 113	TAM 401 x TX10D2230	5.57	4.27	-1.30	NS
TAM 113 x TX10D2230	TAM 111	1.85	0.53	-1.32	NS
TAM 305 x Sturdy 2K	Sturdy 2K	2.93	1.6	-1.33	NS
TAM 113	TAM 112 x TAM 305	6.1	4.77	-1.33	NS
TAM 113 x TAM 401	TX11D3108 x TX10D2230	4.87	3.53	-1.34	NS
TAM 401	TAM 111 x TAM 113	4.33	2.97	-1.36	NS

TAM 113 x TX11D3108	TX11D3108 x TX10D2230	4.93	3.53	-1.40	NS
TAM 401 x TX11D3108	TX11D3108 x Sturdy 2K	4.7	3.3	-1.40	NS
TX11D3108 x TX10D2230	TAM 111 x TX11D3108	3.53	2.1	-1.43	NS
TAM 112 x TAM 305	TX11D3108 x Sturdy 2K	4.77	3.3	-1.47	*
TAM 111 x TX10D2230	TAM 113 x TX10D2230	3.33	1.85	-1.48	NS
TAM 305 x TAM 401	TAM 305 x Sturdy 2K	4.43	2.93	-1.50	*
TX11D3108 x Sturdy 2K	TX11D3108	3.3	1.8	-1.50	NS
TAM 113	TAM 111 x TAM 112	6.1	4.6	-1.50	*
TAM 305 x TX10D2230	TX11D3108 x Sturdy 2K	4.8	3.3	-1.50	*
TAM 111 x TAM 401	TAM 111 x TX10D2230	4.87	3.33	-1.54	*
TAM 113 x TAM 305	TAM 305 x TAM 401	5.97	4.43	-1.54	*
TAM 401	TAM 112 x TX10D2230	4.33	2.77	-1.56	*
TAM 113 x TAM 401	TX11D3108 x Sturdy 2K	4.87	3.3	-1.57	*
TX11D3108 x Sturdy 2K	TAM 112	3.3	1.7	-1.60	*
TAM 112 x TAM 113	TAM 401 x Sturdy 2K	5.57	3.97	-1.60	*
TAM 112 x TAM 401	TX11D3108 x TX10D2230	5.13	3.53	-1.60	*
TAM 112 x TX11D3108	TX11D3108 x TX10D2230	5.13	3.53	-1.60	*
TAM 113 x Sturdy 2K	TAM 305 x TX10D2230	6.4	4.8	-1.60	*
TAM 111 x TAM 112	TAM 111 x TAM 113	4.6	2.97	-1.63	*
TAM 305 x TAM 401	TAM 305 x TX11D3108	4.43	2.8	-1.63	*
TAM 113 x TX11D3108	TX11D3108 x Sturdy 2K	4.93	3.3	-1.63	*
TAM 112 x TX10D2230	Sturdy 2K x TX10D2230	2.77	1.1	-1.67	NS
TX11D3108 x Sturdy 2K	Sturdy 2K	3.3	1.6	-1.70	*

TAM 305 x TX11D3108	Sturdy 2K x TX10D2230	2.8	1.1	-1.70	NS
TAM 113 x TAM 305	TAM 401 x TX10D2230	5.97	4.27	-1.70	*
TAM 113 x Sturdy 2K	TAM 401 x TX11D3108	6.4	4.7	-1.70	*
TX11D3108 x TX10D2230	TX11D3108	3.53	1.8	-1.73	NS
TAM 401 x TX11D3108	TAM 111 x TAM 113	4.7	2.97	-1.73	*
TAM 113	TAM 401	6.1	4.33	-1.77	*
TAM 112 x Sturdy 2K	TAM 111	2.35	0.53	-1.82	*
TAM 305 x TX10D2230	TAM 111 x TAM 113	4.8	2.97	-1.83	*
TAM 111 x TAM 112	TAM 112 x TX10D2230	4.6	2.77	-1.83	*
TX11D3108 x TX10D2230	TAM 112	3.53	1.7	-1.83	*
TAM 305 x Sturdy 2K	Sturdy 2K x TX10D2230	2.93	1.1	-1.83	*
TAM 112 x TAM 401	TX11D3108 x Sturdy 2K	5.13	3.3	-1.83	*
TAM 112 x TX11D3108	TX11D3108 x Sturdy 2K	5.13	3.3	-1.83	*
TAM 112 x TAM 305	TAM 305 x Sturdy 2K	4.77	2.93	-1.84	*
TAM 401 x Sturdy 2K	TAM 111 x TX11D3108	3.97	2.1	-1.87	*
TAM 111 x TAM 305	TAM 111 x TX10D2230	5.23	3.33	-1.90	*
TX11D3108 x TX10D2230	Sturdy 2K	3.53	1.6	-1.93	*
TAM 111 x TAM 401	TAM 305 x Sturdy 2K	4.87	2.93	-1.94	*
TAM 113 x TAM 401	TAM 305 x Sturdy 2K	4.87	2.93	-1.94	*
TAM 305 x TX11D3108	TX10D2230	2.8	0.85	-1.95	*
TAM 112 x TAM 305	TAM 305 x TX11D3108	4.77	2.8	-1.97	*
TAM 113 x Sturdy 2K	TAM 305 x TAM 401	6.4	4.43	-1.97	*
TAM 401	TAM 112 x Sturdy 2K	4.33	2.35	-1.98	*

TAM 112 x TAM 305	TAM 112 x TX10D2230	4.77	2.77	-2.00	*
TAM 113 x TX11D3108	TAM 305 x Sturdy 2K	4.93	2.93	-2.00	*
TAM 113 x TAM 305	TAM 401 x Sturdy 2K	5.97	3.97	-2.00	*
TAM 305	TAM 111 x TX10D2230	5.4	3.33	-2.07	*
TAM 111 x TAM 401	TAM 305 x TX11D3108	4.87	2.8	-2.07	*
TAM 113 x TAM 401	TAM 305 x TX11D3108	4.87	2.8	-2.07	*
TAM 113 x Sturdy 2K	TAM 401	6.4	4.33	-2.07	*
TAM 305 x Sturdy 2K	TX10D2230	2.93	0.85	-2.08	*
TAM 111 x TAM 401	TAM 112 x TX10D2230	4.87	2.77	-2.10	*
TAM 113 x TX11D3108	TAM 305 x TX11D3108	4.93	2.8	-2.13	*
TAM 113 x Sturdy 2K	TAM 401 x TX10D2230	6.4	4.27	-2.13	*
TAM 401 x TX10D2230	TAM 111 x TX11D3108	4.27	2.1	-2.17	*
TAM 111 x TAM 113	TAM 111 x Sturdy 2K	2.97	0.8	-2.17	*
TAM 401 x Sturdy 2K	TX11D3108	3.97	1.8	-2.17	*
TX11D3108 x Sturdy 2K	Sturdy 2K x TX10D2230	3.3	1.1	-2.20	*
TAM 112 x TAM 401	TAM 305 x Sturdy 2K	5.13	2.93	-2.20	*
TAM 112 x TX11D3108	TAM 305 x Sturdy 2K	5.13	2.93	-2.20	*
TAM 401	TAM 111 x TX11D3108	4.33	2.1	-2.23	*
TAM 112 x TX10D2230	TAM 111	2.77	0.53	-2.24	*
TAM 111 x TAM 112	TAM 112 x Sturdy 2K	4.6	2.35	-2.25	*
TAM 305 x TX11D3108	TAM 111	2.8	0.53	-2.27	*
TAM 401 x Sturdy 2K	TAM 112	3.97	1.7	-2.27	*

TAM 112 x TAM 113	TX11D3108 x Sturdy 2K	5.57	3.3	-2.27	*
TAM 111 x TAM 305	TAM 305 x Sturdy 2K	5.23	2.93	-2.30	*
TAM 112 x TAM 401	TAM 305 x TX11D3108	5.13	2.8	-2.33	*
TAM 112 x TX11D3108	TAM 305 x TX11D3108	5.13	2.8	-2.33	*
TAM 112 x TAM 401	TAM 112 x TX10D2230	5.13	2.77	-2.36	*
TAM 112 x TX11D3108	TAM 112 x TX10D2230	5.13	2.77	-2.36	*
TAM 401 x Sturdy 2K	Sturdy 2K	3.97	1.6	-2.37	*
TAM 305 x Sturdy 2K	TAM 111	2.93	0.53	-2.40	*
TAM 112 x TAM 305	TAM 112 x Sturdy 2K	4.77	2.35	-2.42	*
TX11D3108 x TX10D2230	Sturdy 2K x TX10D2230	3.53	1.1	-2.43	*
TAM 305	TAM 111 x TAM 113	5.4	2.97	-2.43	*
TAM 113 x Sturdy 2K	TAM 401 x Sturdy 2K	6.4	3.97	-2.43	*
TAM 111 x TAM 305	TAM 305 x TX11D3108	5.23	2.8	-2.43	*
TAM 113 x TAM 305	TX11D3108 x TX10D2230	5.97	3.53	-2.44	*
TX11D3108 x Sturdy 2K	TX10D2230	3.3	0.85	-2.45	*
TAM 111 x TAM 305	TAM 112 x TX10D2230	5.23	2.77	-2.46	*
TAM 401 x TX10D2230	TX11D3108	4.27	1.8	-2.47	*
TAM 111 x TAM 112	TAM 111 x TX11D3108	4.6	2.1	-2.50	*
TX11D3108 x Sturdy 2K	TAM 111 x Sturdy 2K	3.3	0.8	-2.50	*
TAM 111 x TAM 401	TAM 112 x Sturdy 2K	4.87	2.35	-2.52	*
TAM 401	TX11D3108	4.33	1.8	-2.53	*
TAM 401 x TX10D2230	TAM 112	4.27	1.7	-2.57	*
TAM 305 x TAM 401	TX11D3108	4.43	1.8	-2.63	*

TAM 305	TAM 112 x TX10D2230	5.4	2.77	-2.63	*
TAM 112 x TAM 113	TAM 305 x Sturdy 2K	5.57	2.93	-2.64	*
TAM 401 x TX10D2230	Sturdy 2K	4.27	1.6	-2.67	*
TAM 113 x TAM 305	TX11D3108 x Sturdy 2K	5.97	3.3	-2.67	*
TX11D3108 x TX10D2230	TX10D2230	3.53	0.85	-2.68	*
TX11D3108 x TX10D2230	TAM 111 x Sturdy 2K	3.53	0.8	-2.73	*
TAM 305 x TAM 401	TAM 112	4.43	1.7	-2.73	*
TAM 401	Sturdy 2K	4.33	1.6	-2.73	*
TAM 111 x TAM 112	TAM 113 x TX10D2230	4.6	1.85	-2.75	*
TX11D3108 x Sturdy 2K	TAM 111	3.3	0.53	-2.77	*
TAM 113	TAM 111 x TX10D2230	6.1	3.33	-2.77	*
TAM 111 x TAM 401	TAM 111 x TX11D3108	4.87	2.1	-2.77	*
TAM 112 x TAM 113	TAM 305 x TX11D3108	5.57	2.8	-2.77	*
TAM 112 x TAM 401	TAM 112 x Sturdy 2K	5.13	2.35	-2.78	*
TAM 112 x TX11D3108	TAM 112 x Sturdy 2K	5.13	2.35	-2.78	*
TAM 112 x TAM 113	TAM 112 x TX10D2230	5.57	2.77	-2.80	*
TAM 305 x TAM 401	Sturdy 2K	4.43	1.6	-2.83	*
TAM 401 x Sturdy 2K	Sturdy 2K x TX10D2230	3.97	1.1	-2.87	*
TAM 113 x Sturdy 2K	TX11D3108 x TX10D2230	6.4	3.53	-2.87	*
TAM 111 x TAM 305	TAM 112 x Sturdy 2K	5.23	2.35	-2.88	*
TAM 401 x TX11D3108	TX11D3108	4.7	1.8	-2.90	*
TAM 112 x TAM 305	TAM 113 x TX10D2230	4.77	1.85	-2.92	*
TX11D3108 x TX10D2230	TAM 111	3.53	0.53	-3.00	*

TAM 401 x TX11D3108	TAM 112	4.7	1.7	-3.00	*
TAM 305 x TX10D2230	TX11D3108	4.8	1.8	-3.00	*
TAM 111 x TAM 401	TAM 113 x TX10D2230	4.87	1.85	-3.02	*
TAM 113 x TAM 401	TAM 113 x TX10D2230	4.87	1.85	-3.02	*
TAM 113 x TAM 305	TAM 305 x Sturdy 2K	5.97	2.93	-3.04	*
TAM 305	TAM 112 x Sturdy 2K	5.4	2.35	-3.05	*
TAM 113 x TX11D3108	TAM 113 x TX10D2230	4.93	1.85	-3.08	*
TAM 305 x TX10D2230	TAM 112	4.8	1.7	-3.10	*
TAM 401 x TX11D3108	Sturdy 2K	4.7	1.6	-3.10	*
TAM 113 x Sturdy 2K	TX11D3108 x Sturdy 2K	6.4	3.3	-3.10	*
TAM 401 x Sturdy 2K	TX10D2230	3.97	0.85	-3.12	*
TAM 113	TAM 111 x TAM 113	6.1	2.97	-3.13	*
TAM 111 x TAM 305	TAM 111 x TX11D3108	5.23	2.1	-3.13	*
TAM 401 x TX10D2230	Sturdy 2K x TX10D2230	4.27	1.1	-3.17	*
TAM 113 x TAM 401	TAM 112	4.87	1.7	-3.17	*
TAM 113 x TAM 305	TAM 305 x TX11D3108	5.97	2.8	-3.17	*
TAM 305 x TX10D2230	Sturdy 2K	4.8	1.6	-3.20	*
TAM 112 x TAM 113	TAM 112 x Sturdy 2K	5.57	2.35	-3.22	*
TAM 113 x TX11D3108	TAM 112	4.93	1.7	-3.23	*
TAM 112 x TAM 401	TAM 113 x TX10D2230	5.13	1.85	-3.28	*
TAM 112 x TX11D3108	TAM 113 x TX10D2230	5.13	1.85	-3.28	*
TAM 305	TAM 111 x TX11D3108	5.4	2.1	-3.30	*
TAM 305 x TAM 401	Sturdy 2K x TX10D2230	4.43	1.1	-3.33	*

TAM 113	TAM 112 x TX10D2230	6.1	2.77	-3.33	*
TAM 111 x TAM 305	TAM 113 x TX10D2230	5.23	1.85	-3.38	*
TAM 401 x TX10D2230	TX10D2230	4.27	0.85	-3.42	*
TAM 401 x Sturdy 2K	TAM 111	3.97	0.53	-3.44	*
TAM 401 x TX10D2230	TAM 111 x Sturdy 2K	4.27	0.8	-3.47	*
TAM 113 x Sturdy 2K	TAM 305 x Sturdy 2K	6.4	2.93	-3.47	*
TAM 401	TX10D2230	4.33	0.85	-3.48	*
TAM 401	TAM 111 x Sturdy 2K	4.33	0.8	-3.53	*
TAM 305 x TAM 401	TX10D2230	4.43	0.85	-3.58	*
TAM 401 x TX11D3108	Sturdy 2K x TX10D2230	4.7	1.1	-3.60	*
TAM 113 x Sturdy 2K	TAM 305 x TX11D3108	6.4	2.8	-3.60	*
TAM 305	TX11D3108	5.4	1.8	-3.60	*
TAM 305 x TX10D2230	Sturdy 2K x TX10D2230	4.8	1.1	-3.70	*
TAM 112 x TAM 113	TAM 113 x TX10D2230	5.57	1.85	-3.72	*
TAM 401 x TX10D2230	TAM 111	4.27	0.53	-3.74	*
TAM 113	TAM 112 x Sturdy 2K	6.1	2.35	-3.75	*
TAM 113 x TAM 401	Sturdy 2K x TX10D2230	4.87	1.1	-3.77	*
TAM 111 x TAM 112	TAM 111 x Sturdy 2K	4.6	0.8	-3.80	*
TAM 305	Sturdy 2K	5.4	1.6	-3.80	*
TAM 113 x TX11D3108	Sturdy 2K x TX10D2230	4.93	1.1	-3.83	*
TAM 401 x TX11D3108	TX10D2230	4.7	0.85	-3.85	*
TAM 305 x TAM 401	TAM 111	4.43	0.53	-3.90	*
TAM 305 x TX10D2230	TX10D2230	4.8	0.85	-3.95	*
TAM 113	TAM 111 x TX11D3108	6.1	2.1	-4.00	*
TAM 112 x TAM 401	Sturdy 2K x TX10D2230	5.13	1.1	-4.03	*

TAM 112 x TX11D3108	Sturdy 2K x TX10D2230	5.13	1.1	-4.03	*
TAM 111 x TAM 401	TAM 111 x Sturdy 2K	4.87	0.8	-4.07	*
TAM 113 x TAM 305	TAM 113 x TX10D2230	5.97	1.85	-4.12	*
TAM 401 x TX11D3108	TAM 111	4.7	0.53	-4.17	*
TAM 305 x TX10D2230	TAM 111	4.8	0.53	-4.27	*
TAM 113 x TAM 305	TAM 112	5.97	1.7	-4.27	*
TAM 113	TX11D3108	6.1	1.8	-4.30	*
TAM 113 x TAM 401	TAM 111	4.87	0.53	-4.34	*
TAM 113 x TX11D3108	TAM 111	4.93	0.53	-4.40	*
TAM 111 x TAM 305	TAM 111 x Sturdy 2K	5.23	0.8	-4.43	*
TAM 113	Sturdy 2K	6.1	1.6	-4.50	*
TAM 113 x Sturdy 2K	TAM 113 x TX10D2230	6.4	1.85	-4.55	*
TAM 305	TX10D2230	5.4	0.85	-4.55	*
TAM 305	TAM 111 x Sturdy 2K	5.4	0.8	-4.60	*
TAM 113 x Sturdy 2K	TX11D3108	6.4	1.8	-4.60	*
TAM 113 x Sturdy 2K	TAM 112	6.4	1.7	-4.70	*
TAM 113 x TAM 305	Sturdy 2K x TX10D2230	5.97	1.1	-4.87	*
TAM 113	TX10D2230	6.1	0.85	-5.25	*
TAM 113	TAM 111 x Sturdy 2K	6.1	0.8	-5.30	*
TAM 113 x Sturdy 2K	Sturdy 2K x TX10D2230	6.4	1.1	-5.30	*
TAM 113 x TAM 305	TAM 111	5.97	0.53	-5.44	*
TAM 113 x Sturdy 2K	TAM 111	6.4	0.53	-5.87	*

LSD for 3 reps= 1.47, LSD for 2 reps= 1.79, LSD for unequal reps= 1.77, NS= Not significant, *= Significant at P<0.05

Appendix VI SAS code used to analyze F_2 population for yield per pot

```
data f2;
input Parent1 Parent2 Rep Entry DTH Heads Tillers HT Seeds Grams;
cards;

proc glm;
class entry;
model grams= entry;
run;
```